



Proceedings

ASPE 2012 Summer Topical Meeting

**Precision Engineering and Mechatronics
Supporting the Semiconductor Industry**

June 2012

American Society for

Precision Engineering

P.O. Box 10826, Raleigh, NC 27605-0826
(919) 839-8444 | Fax (919) 839-8039

Proceedings of:

**Precision Engineering and
Mechatronics Supporting the
Semiconductor Industry**

2012 Summer Topical Meeting

June 24 to 26, 2012

Lawrence Berkeley National Laboratory
Berkeley, California, USA

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

Founded in 1986, ASPE provides a new focus for a diverse but important community. Other professional organizations have covered aspects of precision engineering, always as a sideline to their principal goals. ASPE is based on the core of generic concepts necessary to achieve precision in any application; independent of discipline, ASPE intends to be the focus for precision technology, and to represent all facets from research to application

ASPE – The American Society for Precision Engineering
301 Glenwood Avenue, Suite 205, Raleigh, NC 27603
P.O. Box 10826, Raleigh, NC 27605
Telephone: (919) 839-8444 Fax (919) 839-8039
Web site: <http://www.aspe.net>

Preface

This book comprises the proceedings of the 2012 Summer Topical Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE or its editorial staff.

Individual readers of this book and nonprofit libraries acting for them are permitted to make fair use of the material contained in this book to be used in teaching or research; provided they copy said paper in total, as written by the author. Permission is granted to quote excerpts from the scientific or technical works in this book with proper acknowledgment of the source to include: The author's name, the book name, and the ASPE tag line. Reproduction of figures and tables is likewise permitted from the contents of this book, provided that the same acknowledgment of the same source and content is permitted.

Any other type reproduction, systematic copying or multiple reproduction of any material in this book is expressly prohibited except with the written permission of the ASPE editorial staff, addressed to the Society's headquarters.

ISBN 978-1-887706-60-5

2012

American Society for Precision Engineering
301 Glenwood Avenue, Suite 205
Raleigh, NC 27603

Printed in the United States of America

2012 Summer Topical Meeting

Contents

Preface	ii
Contents	iii
Schedule	iv
Foreword	v-vi
Technical Paper Index	vii-x
Technical Papers	3-111
Author Index	113-114
Sustaining Corporate Sponsors	115
Corporate Sponsors	116

2012 ASPE Summer Topical Meeting

Meeting Schedule

	Sunday, June 24 Building 15 Room 253		Monday, June 25 Building 66-Auditorium Room 317C		Tuesday, June 26 Building 66-Auditorium Room 317C
7:00	Registration and Continental Breakfast	7:00	Registration and Continental Breakfast		
8:00	TUTORIAL	8:15	Welcome	8:00	Registration and Continental Breakfast
		8:30	TECHNICAL SESSION I	8:45	Opening Remarks
				9:00	TECHNICAL SESSION V
10:00	Coffee Break	10:00	Coffee Break & POSTERS		
10:30	TUTORIAL CONTINUED	10:30	TECHNICAL SESSION II	10:30	Coffee Break & POSTERS
				11:00	TECHNICAL SESSION VI
12:00	Lunch	12:00	Lunch	12:00	Lunch
1:00	TUTORIAL CONTINUED	1:00	COMMERCIAL SESSION	1:00	TECHNICAL SESSION VII
		2:00	TECHNICAL SESSION III		
2:30	Coffee Break				
3:00	TUTORIAL CONTINUED	3:00	Coffee Break & POSTERS	3:00	Coffee Break & POSTERS
		3:30	TECHNICAL SESSION IV	3:30	TECHNICAL SESSION VIII
5:00		5:00		5:00	
		5:15	Board Buses for Dinner		
6:00	RECEPTION AT HOTEL DURANT	6:00	DINNER AT PYRAMID ALEHOUSE BREWERY	6:00	After Meeting Gathering

Foreword

This topical meeting is a second version of the highly successful meeting held in Spring 2008, Precision Mechanical Design and Mechatronics for Sub-50nm Semiconductor Equipment. (Proceedings can be viewed at http://aspe.net/publications/Spring_2008/Spring_08.html).

The meeting venue will again be Lawrence Berkeley National Laboratory, where Senajith (Seno) Rekawa and his wonderful staff have facilitated a majestic auditorium very conducive to an interactive atmosphere between the speaker and the audience. Berkeley Lab is a multidisciplinary national laboratory located on a hillside directly above the campus of the University of California at Berkeley.

The semiconductor equipment industry is presently facing a number of interesting challenges. At the same time they are faced with continuous “shrink and growth”. The Critical Dimensions will go below 25 nm while the size of the silicon wafer will grow to 450 mm diameter.

The smaller CD cannot be imaged with regular optical systems and thus the search and development of alternative approaches must be taken up. The following list gives an impression of the potential roads to smaller CD's:

- Double Patterning Immersion Lithography
- Extreme Ultraviolet Lithography (EUVL)
- Massive Parallel E-beam, Maskless Lithography
- Nano-Imprint Lithography

The challenges are not only in the field of imaging but will also influence inspection and metrology equipment. At the same time, the transition to 450 mm wafers will influence all equipment suppliers. As many elements will have to be redesigned for this transition this is the moment where companies can revisit the architecture for their equipment. The next generation 450 mm tools will have to be capable for the CD level of the future, more productive and be the most cost effective.

Clearly this is a very challenging time for System Engineers involved in the creation of the future products for their companies. This topical meeting offers them a platform to exchange results of research results, to hear about developments in component technologies and to broaden their view on the wealth of system concepts that might be used.

The general intent is to bring together engineers and scientists from the semiconductor industry with members of the American Society for Precision Engineering. These groups partly overlap, but in many other cases, there is a novel opportunity to share advances, challenges, and seek mutual solutions in attaining high levels of precision in manufacturing.

The objective of this meeting is to enable a technical dialogue between engineers directly supporting the semiconductor industry and the broader field of precision engineering. The focus of this meeting will be on issues regarding precision mechanics and control, recognizing that detailed issues of lithographic processing, such as resist development, are well-represented in other venues. The intended semiconductor technology audience includes current lithographic tool makers, and also related technology developers, such as in mask writing, opto-mechanics, and future lithographies such as EUV, maskless, and nano-imprint.

A full-day tutorial on Sunday, June 24 will give participants the opportunity to become acquainted with both fundamentals and recent developments in the field of semiconductor equipment. The focus will be on system dynamics and the influence of key sources of error, including thermal loading and floor vibrations. The tutorial will be an excellent learning experience for precision and semiconductor engineers.

The 2012 Summer Topical Meeting will span 2 days with technical presentations, with time allocated for professional networking and brief commercial presentations and general announcements. We have reserved blocks of rooms at local hotels, and have planned a reception as well as an enjoyable dinner at a local venue. Please refer to aspe.net for more details.

Technical Topics

- CD and overlay error budgets
- Motion control and synchronization in step-and-scan lithography
- Actuator and sensor innovations
- Motion control requirements for nano-imprint, maskless, and other new processes
- Stage design and control for high-g and high throughput requirements
- Design and testing of advanced rotational degrees of freedom
- Thermal management
- Precision engineering in clean and/or vacuum environments
- Reticle and wafer chucking
- Sensors for alignment and active motion control
- Advanced motion control
- System qualification and reliability
- Qualification of ultra-precision stages and the application of Standards
- Fixturing of optical components
- Measurement and control of vibration and settling time
- Active and passive strategies for damping
- Metrology and diagnostics of errors
- Alignment strategies, e.g. for the mask stage, wafer stage, imaging optics
- Synergistic areas of microfabrication, grating manufacture, LIGA
- Equipment design for 450 mm wafers

2012 Summer Topical Meeting Program Committee:

Meeting Co-Chairmen:

John S. Taylor

Lawrence Livermore National Laboratory

Jan van Eijk

MICE BV; Delft University of Technology

Scientific Committee:

Luis A. Aguirre, 3M Company

Pete J. Fitsos, Lawrence Livermore National Laboratory

Xiaodong Lu, The University of British Columbia

Stephen J. Ludwick, Aerotech, Inc.

Richard C. Montesanti, Lawrence Livermore National Laboratory

Robert-Han Munnig Schmidt, Delft University of Technology and ASML Netherlands BV

Senajith B. Rekawa, Lawrence Berkeley National Laboratory

Marcel J. M. Renkens, Philips Innovation Services

Jeffrey W. Roblee, AMETEK – Precitech, Inc.

Theo A. M. Ruijl, MI-Partners

Mark L. Schattenburg, Massachusetts Institute of Technology

Stefan Scherer, Alicona Imaging GmbH

Pradeep K. Subrahmanyam, KLA Tencor

David L. Trumper, Massachusetts Institute of Technology

Technical Sessions

Welcome and Opening Remarks

Monday, June 25, 2012, 8:15AM - 8:30AM

John S. Taylor (Lawrence Livermore National Laboratory)

Session I

Semiconductor Industry Drivers

Monday, June 25, 2012, 8:30AM - 10:00AM

Session Chairs: John S. Taylor (Lawrence Livermore National Laboratory) and Jan van Eijk (MICE BV and Delft University of Technology)

- 1. Pico(meters) to the People**
Golda, J. (Intel Corporation) 3
- 2. Creating an EUV Mask Microscope for Lithography Generations Reaching 8 nm**
Goldberg, K. A.; Mochi, I.; Benk, M. P.; Allezy, A. P.; Smith, N. S.; Cork, C. W.; Cork, W.; Macdougall, J.; Chao, W. L.; Anderson, E. H.; Naulleau, P.; Rekawa, S. B. (Lawrence Berkeley National Laboratory); Acome, E.; van Every, E. (Advanced Design Consulting USA, Inc.) and Milanovic, V. (Mirrorcle Technologies, Inc.) 4
- 3. Semiconductor Lithography: Enabling Production Beyond 22 nm**
Binnard, M. (Nikon Research Corporation of America) and Shibasaki, Y.; Hamatani, M.; Wakamoto, S.; Shiba, Y.; Uehara, Y.; Fujiwara, T. (Nikon Corporation) 8

Session II

Emerging Lithographic Technologies

Monday, June 25, 2012, 10:30AM - 12:00PM

Session Chairs: Pradeep K. Subrahmanyam (KLA Tencor) and Mark L. Schattenburg (Massachusetts Institute of Technology)

- 1. Linear Stage and Metrology Architecture for Reflective Electron Beam Lithography. (REBL)**
Ummethala, U.; Hale, L. C.; Clyne, J.; Nayfeh, S. A.; Williams, M. E.; Di Regolo, J. A. (KLA Tencor Corporation) and van Lievenooogen, A.; van Loo, J. (Philips Innovation Services) 16
- 2. Plasmonic Imaging Lithography Machine (PILM)**
Saad, M. E.; Hocken, R. J. (University of North Carolina at Charlotte) 17
- 3. Status of Jet and Flash Imprint Lithography Steppers for Sub-25nm Semiconductor Memory Manufacturing**
Mokaberi, B.; Nimmakayala, P.; Ye, Z.; Schumaker, P.; Choi, J.; LaBrake, D. (Molecular Imprints, Inc.) and Sreenivasan, S. V. (The University of Texas at Austin and Molecular Imprints, Inc.) 22

Commercial Session

Monday, June 25, 2012, 1:00 PM - 2:00 PM

Session Chairs: Pete J. Fitsos (Lawrence Livermore National Laboratory) and Luis A. Aguirre (3M Company)

Session III

Stage Design Strategies

Monday, June 25, 2012, 2:00PM - 3:00PM

Session Chairs: Marcel J. M. Renkens (Philips Innovation Services) and Jeffrey W. Roblee (AMETEK-Precitech, Inc.)

- 1. Recent Advancements in Long-Travel, Nanoscale Optic/Substrate Positioning with Quantitative Measurement of Long-Term Stability**
Jordan, S. C. (PI (Physik Instrumente) L.P.) 27
- 2. Conceptual Design of Mechatronic Machine Components Using Topology Optimization**
Vandyshev, K.; Langelaar, M.; van Keulen, F; (Delft University of Technology) and van Eijk, J. (MICE, BV and Delft University of Technology) 32

Session IV

Stage Characterization and Metrology

Monday, June 25, 2012, 3:30PM - 5:00PM

Session Chairs: Xiaodong Lu (The University of British Columbia) and Stephen J. Ludwick (Aerotech, Inc.)

- 1. Fiber-Coupled 3-DOF Interferometer for EUV Lithography Stage Metrology**
Ellis, J. D.; Gillmer, S.; Wang, C.; Smith, R. (University of Rochester) and Woody, S. C.; Tarbuton, J. (InSituTec, Inc.) 36
- 2. Dimensional Metrology of Plasmonic Nanolithography Machine**
Ni, K.; Hocken, R. J. (University of North Carolina at Charlotte) 42
- 3. Vibration Spectra and Asynchronous Error Motion of Ultra-Precision Air Bearing Spindles**
Knapp, B. R.; Oss, D. D.; Arneson, D. A.; Liebers, M. J. (Professional Instruments Company, Inc.) and Marsh, E. R. (The Pennsylvania State University) 45

Opening Remarks

Tuesday, June 26, 2012, 8:45AM - 9:00AM

John S. Taylor (Lawrence Livermore National Laboratory)

Session V

Mechatronic Actuators and Motors

Tuesday, June 26, 2012, 9:00AM - 10:30AM

Session Chairs: Richard C. Montesanti (Lawrence Livermore National Laboratory) and Marcel J. M. Renkens (Philips Innovation Services)

- 1. Moving-Magnet Planar Motors for Next-Generation Lithography**
Lu, X.; Usman, I. (The University of British Columbia) 49
- 2. Recent Developments and Comparative Evaluation of Lorentz and Reluctance Actuators for High Precision Semiconductor Equipment Stages**
Toma, A.; Sahin, F.; Renkens, M. J. M. (Philips Innovation Services) 53
- 3. An Alternative Permanent Magnet Brushless Motor Architecture**
Safreno, T. F.; Kelley, T.; Goldsmith, R. J. (Trust Automation, Inc.) 59

Session VI

Mechanical Lithography

Tuesday, June 26, 2012, 11:00AM - 12:00PM

Session Chairs: Luis A. Aguirre (3M Company) and Stefan Scherer (Alicona Imaging GmbH)

- 1. High-Speed Creation of Nanometer-Scale Features - Nanocoining**
Dow, T. A.; Zdanowicz, E. M.; Nowak, W. J. (North Carolina State University). 64
- 2. Mechanical Patterning of Optical Microstructures**
Brinksmeier, E.; Gläbe, R.; Schönmann, L; Meier, A. (University of Bremen) 68

Session VII

Robust Control Strategies

Tuesday, June 26, 2012, 1:00PM - 3:00PM

Session Chairs: Stephen J. Ludwick (Aerotech, Inc.) and Pradeep K. Subrahmanyam (KLA Tencor)

- 1. High Performance Motion And Vibration Control for Precision Machines**
Tsao, T.-C.; Wang, Y.; Chu, K. (University of California at Los Angeles) 73
- 2. Coordinating Digital I/O with Precision Motion**
Wilson, C. S. (Delta Tau Data Systems, Inc.) 76
- 3. Engineering Interpretation of Eigenvector Sensitivities Using Normalization**
Hooijkamp, E. C.; Peters, H. J.; van Keulen, F. (Delft University of Technology) and van Eijk, J. (MICE BV and Delft University of Technology) 80
- 4. Robustness Analysis of Dynamics and Control – A New Method to Support High Performance Optical Manipulator Design**
Schönhoff, Ulrich (Carl Zeiss SMT GmbH). 83

Session VIII

Enabling Mechatronic Technologies

Tuesday, June 26, 2012, 3:30PM - 5:00PM

Session Chairs: Theo A. M. Ruijl (MI-Partners) and
Senajith B. Rekawa (Lawrence Berkeley National Laboratory)

- 1. Parallel Kinematics and 6-DOF Active Damping in High Accuracy Vacuum Applications**
Glöss, R.; Mock, C. D. (Physik Instrumente (PI) GmbH & Co. KG) and
Oberfell, J. (PI miCos GmbH) 89
- 2. Optomechanical Characterization of Large Wafer Stepper-Optics with Respect to Centering Errors, Lens Distances and Center Thicknesses**
Stickler, D.; Lüerß, B.; Langehanenberg, P.; Heinisch, J.;
Dumitrescu, E. (TRIOPTICS GmbH) 91
- 3. Closed Loop Thermal Control of a Lithographic Optical Component**
Saathof, R.; Haber, A.; Spronck, J. W.; Verhaegen, M.; Munnig Schmidt, R. H.
(Delft University of Technology) 95

Poster Sessions

Monday, June 25, 2012, 10:00AM - 10:30AM and 3:00PM - 3:30PM

Tuesday, June 26, 2012, 10:30AM - 11:00AM and 3:00PM - 3:30PM

- 1. Design and Verification of a Coarse Stage of Planar Motor Levitating by Air Bearing**
Zhang, Z.; Wu, L.; Zhang, X.; Chi, F.; Cheng, J. (Shanghai Micro Electronics
Equipment Co., Ltd.) 101
- 2. Flexure Based Microscope Objective**
Stockbridge, C. R.; Köklü, F. H.; Ramsay, E.; Lu, Y.; Ünlü, M. S.; Goldberg, B. B.;
Bifano, T. G. (Boston University). 105
- 3. Extending All-Optical Processes to the 11nm (20nm Half-Pitch) Technology Node**
Hendel, R. H.; Peterson, J. S.; Markle, D. A.; Raub, A. K.; Greenway, R. T. (Periodic
Structures, Inc.) and Smayling, M. C. (Tela Innovations, Inc.) 109



Technical Papers

PICO(METERS) TO THE PEOPLE

Janice M. Golda
Lithography Capital Equipment Development
Intel Corporation
Santa Clara, California

ABSTRACT

Realizing the vision that “this decade we will create and extend computing technology to connect and enrich the lives of every person on earth” presents many challenges in increasing device density, shrinking cost per function, and increasing velocity of business. Delivering any one of these is no simple task, and delivering all three is a formidable engineering challenge.

The International Technology Roadmap for Semiconductors (ITRS) articulates device scaling trends and takes us from the 22nm logic node in production today to single digit nanometers this decade. On the patterning front, achieving this will require a toolbox of lithography techniques and enhancements including multiple patterning, EUV lithography, complex masks, advanced materials, and computational lithography. Both minimum feature size and pattern placement are key parameters to achieve scaling; resolution alone is not sufficient. Metrology and inspection technologies must be able to measure the size and position of complex features as well as identify defects which may impact yield of both masks and wafers. At <10nm nodes, error budgets will become sub-nanometer, meaning that error budget components at the subsystem level will (generously) be fractions of nanometers, requiring innovation at the component level.

Realizing the scaling roadmap is the first driver in decreasing cost per function, followed closely by increasing productivity. Producing more good die per hour requires reaching into the toolbox of equipment productivity and wafer size scaling to 450mm. Both of these will need to occur in parallel with continuing device scaling; achieving sub-nanometer precision must be done at ever increasing speed and over larger distances, requiring innovation in integrating complete solutions.

The third aspect, velocity, is important both at the tool level and at the macro level of total leadtime from order to delivery. Equipment solutions that can most quickly adapt to frequently changing customer demands are highly desirable, providing yet another “market” for innovation in precision engineering.

CREATING AN EUV MASK MICROSCOPE FOR LITHOGRAPHY GENERATIONS REACHING 8 NM

Kenneth A. Goldberg¹, Iacopo Mochi¹, Markus P. Benk¹, Arnaud P. Allezy¹,
Nathan S. Smith¹, Carl W. Cork¹, William Cork¹, James Macdougall¹,
Weilun L. Chao¹, Erik H. Anderson¹, Patrick P. Naulleau¹, Eric Acome²,
Eric Van Every², Veljko Milanovic³ and Senajith B. Rekawa¹

¹Lawrence Berkeley National Laboratory, Berkeley, California, USA

²Advanced Design Consulting USA Inc., 126 Ridge Rd, Lansing NY 14882, USA

³Mirrorcle Technologies, Inc., 2700 Rydin Road, Unit F, Richmond, CA 94804

INTRODUCTION

We are creating a synchrotron-based extreme ultraviolet (EUV, 13.5-nm wavelength) microscope to support advanced photomask research for the semiconductor industry. The new microscope will serve photolithography generations to the year 2020 and beyond, when printed feature sizes are expected to fall below 10 nm. Called *SHARP* (the SEMATECH High-NA Actinic Reticle review Project), the microscope is designed to emulate the optical properties of current and future EUV lithography tools, enabling the study of mask defects, pattern architectures, optical proximity correction, phase-shifting patterns, and more [1].

EUV lithography, a pattern-transfer technology based on 13.5-nm-wavelength light, is a leading contender for the commercial mass-production of several generations of computer chips within this decade. In this wavelength range, all materials are highly absorptive, so optical systems must operate in high vacuum and optical elements are formed from glancing-incidence mirrors, multilayer-coated *Bragg reflector* mirrors, or from nano-patterned, diffractive optical elements. Photomasks, which carry integrated-circuit master patterns, are made from an atomically-smooth low-thermal-expansion glass substrate (typically 6 x 6 x 1/4 inches) with a reflective, Mo/Si multilayer coating, topped with a patterned absorber layer. During printing, the image of the photomask pattern is projected onto a photoresist-covered wafer with 4x demagnification.

Arguably, the widespread adoption of EUV lithography has been delayed by limited light-source power and the unavailability of defect-free masks. Owing to their highly wavelength-specific optical properties, the creation of production-quality masks relies upon dedicated

EUV-wavelength mask-blank inspection and pattern-imaging tools. Currently, commercial tools are several years from deployment. This delay provides an opportunity for an industry/government partnership—SEMATECH together with Lawrence Berkeley National Laboratory (LBNL)—to create and operate the *SHARP* microscope as a research tool that will begin operations in early 2013.

SHARP will be the first short-wavelength microscope to combine lossless, customizable coherence control [2] with zoneplate-lens imaging; and, it will be the first to use a dynamic, MEMS-based EUV mirror element. The central concept of diffraction-limited EUV imaging with zoneplate lenses has been demonstrated [3]. Ultimately, we seek to measure the detailed properties of mask patterns and features that are as small as 24 nm using objective lenses that emulate mask-side numerical aperture (NA) values up to 0.156. (This is equivalent to 6-nm wafer features and 0.625-NA imaging.)

SYSTEM DESCRIPTION

The system specifications can be divided into the optics (illuminator, and imaging), and the mechanical systems required to support them. Achieving high signal-to-noise ratios depends on delivering the maximum possible light-flux into the small imaging region. To that end, *SHARP*'s simplified design contains only essential optical elements. Mechanically, the central challenge is to achieve sub-5-nm stability between the mask and the objective lens during 1–5-second exposures, a level that is required for accurate pattern measurements.

The Source and Illuminator

The *SHARP* microscope is powered by a synchrotron bending-magnet beamline at LBNL's Advanced Light Source, with a monochromator

that provides tunable wavelength and bandwidth. At its focus, the beamline delivers 14 μW of EUV power in a bandwidth, $E/\Delta E = 1000$, focused to a spot size of approximately 250 μm with horizontal and vertical angular divergences of 1.85 and 4.36 mrad, respectively. (See Fig. 1.) A four-jaw slit is placed 2.5 m upstream of focus to decrease the beam divergence for finer coherence control when necessary. A second four-jaw slit, just upstream of the focus, blocks stray light and allows us to cut the lateral size of the beamline's focus, and thus the size of the illumination spot on the mask.

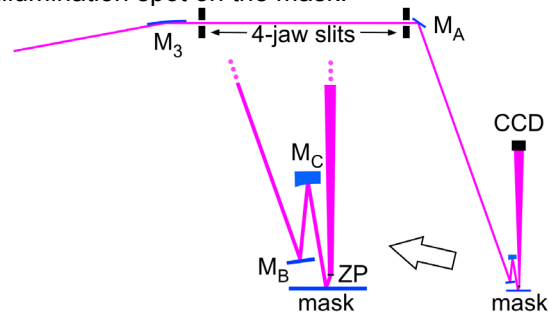


FIGURE 1. The beam path through the SHARP microscope. Inset detail shows a schematic of the M_B , M_C , the mask and the zoneplate (ZP) lens positions. The intermediate focus is on M_A .

Illumination Coherence Control

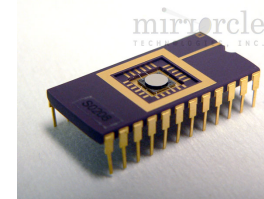
To improve pattern modulation at small feature sizes, modern photolithography relies on illumination coherence control, achieved by tailoring the angular pattern of the incident light. Effective mask microscopes must emulate illumination conditions similar to printing tools. In the SHARP microscope, coherence control is achieved with a *Fourier-domain illuminator* [2] that is designed to take the narrow, static solid-angle of the synchrotron light and dynamically fill arbitrary angular patterns during the exposures, while preserving flux. The illuminator has three mirrors we refer to as M_A , M_B and M_C , that together produce a 10x demagnification of the beamline's intermediate focus and expand the angular range of light incident on the mask up to nearly 19° off-axis (encompassing central-ray angles of 6° to 10°, or more.)

The 10x demagnification reduces the beamline's 250- μm intermediate focus to a size that matches the microscope's typical field of view. Furthermore, the demagnification provides a 10x amplification of the range of ray angles leaving M_C , simplifying the design of the illuminator.

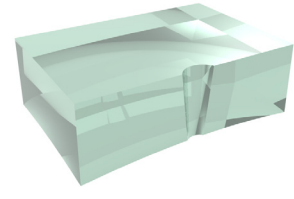
Dynamic EUV MEMS Mirror, M_A

The flat M_A mirror is a gimbal-less dual-axis, scanning MEMS device made from single-crystal silicon and integrated onto a dual inline "DIP24" package (see Fig. 2). Working with *Mirrorcle Technologies* of Richmond, California [4], we have developed a novel EUV-reflective version that can scan arbitrary angular pupil-fill patterns at speeds up to 3 kHz. The beamline's intermediate focus on M_A forms a virtual source for the illuminator that is imaged onto the mask surface by the elliptical M_C mirror.

2



3



FIGURES 2 and 3. (2) Mirrorcle Technologies MEMS mirror, M_A . (3) Model of the elliptical M_C .

M_B and M_C Mirrors

The ellipsoidal mirror M_C is the heart of the illuminator. (See Fig. 3.) It is designed for point-to-point imaging—every ray of light leaving the intermediate focus on M_A reaches a single point on the mask plane. The M_C mirror is being fabricated to EUV surface-finish tolerances: 0.15-nm RMS, with slope errors below 25 μrad . Mirror M_C is wide in the transverse direction, enabling azimuthal rotation of the angle of incidence by $\pm 25^\circ$. A conical hole in the one edge makes room for the upward beam path from the zoneplate to the CCD camera. The flat M_B is a folding mirror that directs the beam upward into M_C so the central angle of incidence on M_C is 10°. M_B keeps the incidence angles on M_C close to normal, simplifying M_C 's multilayer coating.

The M_C mirror also acts as an illumination uniformity scanner. Mounting M_C on a two-axis, tip-tilt stage with a peak frequency of 200 Hz enables us to steer the illumination focal point in a programmed manner across the small field of view. The total angular range of the tip-tilt stage is limited to 50 μrad , small enough not to interfere with the angular illumination patterns created for coherence control.

Fresnel Zoneplate Objective Lenses

Fresnel zoneplate lenses, (typically 100- μm diameter) project the image of the illuminated mask surface onto a 1" EUV CCD detector with high magnification. More than 70 different

lenses, which are binary holograms of high (diffraction-limited) wavefront quality, are patterned in an array in a gold absorber layer on a thin silicon-nitride membrane. The array is fabricated using electron-beam lithography [5].

The zoneplates are single, off-axis lenses of various focal lengths and numerical apertures ranging from 0.0625 to 0.156. Lenses are designed for several central-ray angles and with different azimuthal rotations to mimic illumination conditions across a ring-shaped field of view in an EUV printing tool.

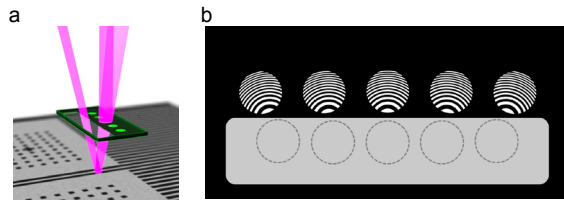


FIGURE 4. (a) Schematic of the beam path incident on and reflected by the mask, and then imaged by a zoneplate within a linear array. (b) A schematic of an array of off-axis zoneplates designed for 5 different azimuthal orientations.

For zoneplates, aberration-free imaging occurs only at the center of the field of view. The width of the *sweet spot* typically covers several microns, large enough for localized defect and pattern studies of interest.

Power is critical to high-quality imaging. For a constant magnification ratio and NA, reducing the focal length shrinks the zoneplate diameter, reduces the number of zones, and thus allows a larger illumination bandwidth to be used. Since power from the beamline is proportional to the bandwidth, for constant exposure level the exposure time is proportional to the focal length. We set the nominal focal length to 500 μm knowing we could adjust both the focal length and the distance to the CCD to achieve 4x higher magnification, if necessary.

Pupil-fill Monitor

Accurate control of the mask illumination requires feedback. Space constraints in the vicinity of the illuminator's focus complicate the development of solutions above the mask plane. The limited photon flux available for conversion to visible-light motivates the positioning of scintillators within a few mm of focus, where the beam is concentrated, yet not so close that the angular pattern is unresolved. Our solution is to bond a thin (5 or 10 μm) YAG scintillator directly to the

surface of an upward facing, visible-light CCD camera that is held on the mask stage. In this configuration, the monitor could be used to assess both M_C focusing (measured in the mask plane) and the pupil-fill angular distribution (below mask plane).

Visible-light Mask Microscope

An *in-situ* visible-light microscope with sub-3- μm resolution and a 1.4 x 1.0 mm field of view simplifies mask navigation, using pattern features and fiducial marks to improve position accuracy. The microscope is based on a long-working distance, 0.14-NA objective with an infinite conjugate, and a relay optical system that projects the image to a CCD camera, positioned above the chamber lid. The optical components are installed in a tube that projects downward into the vacuum chamber from above, with a window at the bottom.

Mechanical System Design

For high-magnification, nano-scale imaging, mechanical stability during multi-second exposures is the most important factor for success. Specifically, SHARP requires a sub-5-nm relative position of the mask and zoneplate during exposure. Thus the overall mechanical design is focused on the in-vacuum vibration isolation of the mask and zoneplate stages, achieved within a noisy experimental hall, in close proximity to pumps and other equipment.

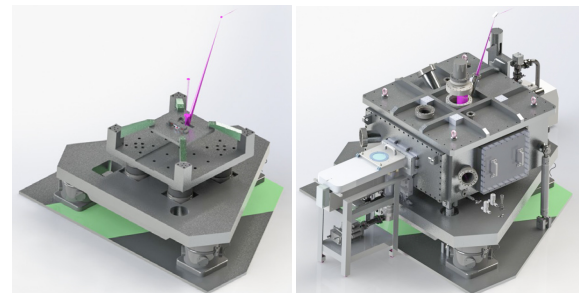


FIGURE 5. (Left) CAD model of SHARP's vibration-isolation system. (Right) Model of the assembled system. The beam path is shown in magenta. The green stripe represents the location of a buried grade beam.

Vibration Isolation

The design begins with a grouted, level floor plate that provides a common base for the chamber and the vibration-isolated platform. (See Fig. 5.) This plate bridges a buried grade beam that is a strong source of localized floor vibrations. Studies showed floor vibration levels of 10 nm integrated RMS displacement above 2

Hz. Three TMC STACIS® 2100 active piezoelectric vibration cancellation systems support a rigid, 4-inch-thick, triangular aluminum plate in the space below the vacuum chamber. The system has an effective active resonant frequency of 0.5 Hz—the transmissibility at resonance is below 1.1 and it is designed to provide 90% isolation at 2 Hz. Inside the vacuum chamber, the unified mask and zoneplate stage support structure is attached to this aluminum plate through the bottom of the chamber using four pillars and flexible bellows. The chamber is independently supported by six struts tied to the floor plate.

Mask and Zoneplate Stage Support Frame

The mask and zoneplate array move independently, on separate xyz stages. The xy mask stage travel exceeds 200 mm, enabling us to reach every point on the mask surface. The xyz zoneplate stage hangs down from a plate located above the mask.

Mask Loading, Holding and Transfer

Mask loading occurs through a conventional robotic load-lock from *Transfer Engineering, Inc.* The mask is held onto the mask stage using a spring-loaded tab system. This system provides lateral position and angle repeatability of approximately 10 μm and 50 μrad . The gravitational sag of the mask supported in this manner induces an apparent tilt at the edges of the mask that is predicted to be below 16 μrad —within the 500 μrad mask-tilt specifications required for zoneplate alignment.

Zoneplate Holder

The small zoneplate wafer ‘chips’, containing the lens arrays, will be held magnetically, flush to a level glass mounting piece using embedded magnets and a thin, electroplated Ni coating on the back side of the zoneplate array ‘chips.’ This technique will enable us to use very short zoneplate focal lengths (100–250 μm) without the risk of bumping the mask surface on a downward-protruding clip of some kind. A zoneplate loading and unloading system will be installed on the mask z stage to exchange zoneplates without breaking vacuum.

Particle and Light Baffles

It is the nature of photomasks, the carriers of nano-scale patterns, to be extremely vulnerable to particle contamination. Care has been used in the selection of stages and components to avoid particle generation wherever possible, and to shield the critical components from direct expo-

sure to particles where possible. During its time within the chamber, the mask is protected from particles, held below a thin metal sheet, with openings only in the two critical locations where observation and inspection takes place: for the EUV zoneplate and the visible-light microscope.

Owing to the extreme sensitivity of the EUV CCD camera to visible and infrared light, internal light emissions from stage encoders and vacuum ion gauges, for example, must be curtailed, and blocked. Magnetic encoders, low heat stages, and cold cathode vacuum gauges were selected to reduce light leaks and provide the darkest possible internal environment.

ACKNOWLEDGMENTS

Plans for SHARP have grown from experience operating and upgrading its predecessor, the SEMATECH Berkeley Actinic Inspection Tool (AIT). These projects owe a debt of gratitude to semiconductor industry and engineering research leaders, and to previous team members including John Taylor (LLNL), Anton Barty (DESY), Yanwei Liu (KLA Tencor), C. Drew Kemp, Obert Wood (GlobalFoundries), and David Chan (SEMATECH).

This work was funded by SEMATECH under Agreement No. LB08005006, and is performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Berkeley National Laboratory under management and operating contract DE-AC02-05CH11231.

REFERENCES

- [1] Goldberg, K A, et al., An EUV Fresnel zoneplate mask-imaging microscope for lithography generations reaching 8 nm, *Proc. SPIE* 7969, 79691O (2011).
- [2] Naulleau, P, et al. Fourier-synthesis custom-coherence illuminator for extreme ultraviolet microfield lithography, *Appl. Opt.*, 42 (5), 820 (2003).
- [3] Mochi, I, et al., Improving the performance of the Actinic Inspection Tool with an optimized alignment procedure, *Proc. SPIE* 7271, 727123 (2009).
- [4] Mirrorcle Technologies, Inc., <http://www.mirrorcletech.com>
- [5] Chao, W, Real space soft x-ray imaging at 10 nm spatial resolution, *Opt. Exp.* 20 (9) 9777 (2012).

Semiconductor Lithography: Enabling Production Beyond 22 nm

Mike Binnard¹, Yuichi Shibasaki², Masato Hamatani²,
Shinji Wakamoto², Yuji Shiba²,
Yusaku Uehara², Tomoharu Fujiwara²

¹Nikon Research Corp. of America

²Nikon Corporation



FIGURE 1. Nikon's S621D ArF Immersion scanner.

INTRODUCTION

Semiconductor lithography is a demanding application for Precision Engineering. State of the art lithography tools, such as the Nikon S621D shown in Figure 1, achieve “almost impossible” levels of performance in imaging quality, focus control, overlay, and productivity. Providing this level of performance is a vital part of enabling the semiconductor industry to continue advances in device performance and cost.

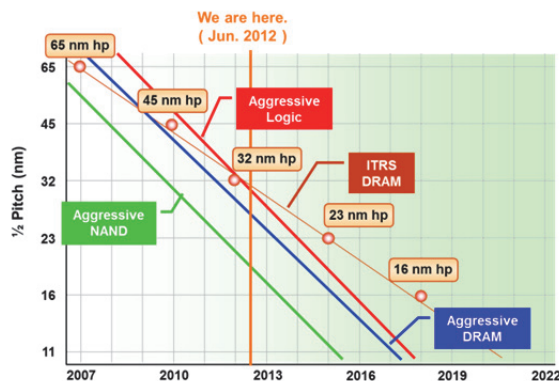


FIGURE 2. ITRS Roadmap for 2011.

Moore's Law is a well-known, self-fulfilling prophecy that has driven the semiconductor

industry for decades. As shown in Figure 2, the industry is constantly working to reduce the minimum feature size, or half-pitch (hp) of printed patterns. Leading edge wafers currently in production have line-space patterns with hp well under 32 nm. This is a remarkable achievement since the wavelength used in these exposures is 193 nm, and because the exposure occurs while the reticle and wafer are both moving at high speed. 10 nm features are only a few years away, which means the engineering challenges will not get easier any time soon.

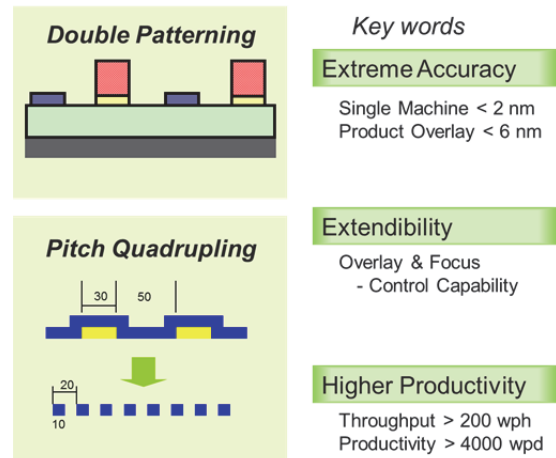


FIGURE 3. Requirements for 22nm and beyond. Double Patterning and future processes, such as Pitch Quadrupling, require improved performance.

INDUSTRY REQUIREMENTS

The fundamental equation for lithography resolution is the Rayleigh Criterion:

$$R = \frac{k_1 \lambda}{NA}$$

Resolution, R , is determined by the wavelength, λ , of the exposure light, the Numerical Aperture, NA , of the projection lens, and a process factor, k_1 . With available technology, all of these factors are now at their practical limitations. The wavelength is 193 nm from ArF excimer lasers,

the NA of immersion systems is limited to about 1.35 by the index of refraction of the available materials, and the k_1 factor is around 0.3, only slightly above the theoretical limit of 0.25. These values create a resolution limit between 40 and 45 nm.

To make smaller features, semiconductor companies are now using Double Patterning (DP) techniques which can create repetitive structures with features of 22nm or less, but require more expensive wafer processing. As illustrated in Figure 3, these processes place increased requirements on the performance of the lithography tools.

To continue the improvement of lithography capability, Nikon and our competitors need to continue providing tools that offer performance improvements in several key areas:

- **Imaging Quality.** Image quality, including resolution and Critical Dimension Uniformity (CDU), is primarily controlled by creating nearly perfect projection optics.
- **Focus control.** Properly focusing the image on the wafer is complicated by the topology of the wafers and the limited Depth of Focus available, typically on the order of 10's of nm.
- **Overlay control.** Placing semiconductor patterns in precise alignment with existing layers on the wafers is critical to making functional devices. Overlay tolerances are typically around 10% of the minimum feature size.
- **Throughput.** Lithography tools and the lithography process are expensive. To produce cost-competitive products, chip companies need to amortize lithography costs over a large number of wafers, which requires very fast machines.
- **Productivity.** Cost-competitive mass production requires lithography tools that can run reliably and consistently.

Meeting the requirements in each of these areas requires significant engineering effort and good Precision Engineering principles.

IMAGING QUALITY

There are many aspects to creating a “good” image of a semiconductor device. Lithography tool suppliers like Nikon need to provide images with the best possible resolution, and with consistent imaging within each die (chip) and across every wafer.

Resolution

The most critical aspect to achieve the best-possible resolution is building a projection lens with minimum aberration of the optical wavefront. State of the art lithography lenses are the most perfect optical instruments ever built. Nikon and our competitors are continuing to make improvements in lens design, manufacturing capabilities, and assembly processes to offer improved performance to our customers.

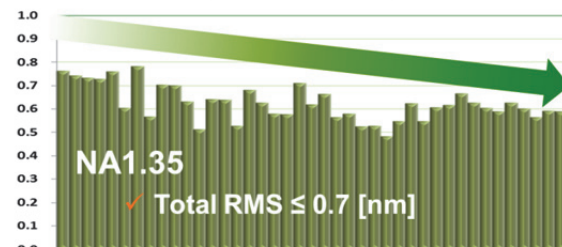


FIGURE 4. Wavefront aberration of Nikon's NA1.35 projection lenses shows excellent results and steady improvement over time.

As shown in Figure 4, Nikon's NA1.35 projection lenses provide a total wavefront aberration under 0.7 nm RMS. Reaching this level of performance requires sophisticated lens manufacturing and polishing techniques to produce nearly perfect optics. The opto-mechanical design of the lens barrel must provide an optimum balance of stiff support (to control positioning and reduce vibration) with kinematic constraint (to prevent deformation of the optical surfaces). In addition there are many sensors and actuators within the lens assembly to provide automatic control of aberration performance.

Critical Dimension Uniformity

A second critical measurement of imaging quality is the Critical Dimension Uniformity (CDU) of the exposed patterns. Lithography tools offer many automatic adjustments within

the positioning stages, the projection optics, the illumination optics, and the process-control of the tool to improve CDU.

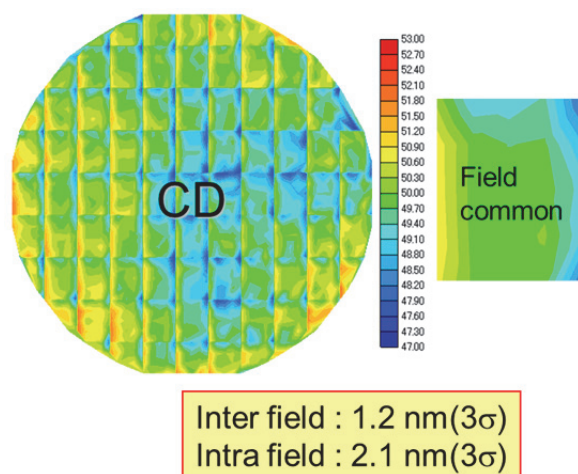


FIGURE 5. Critical Dimension (CD) measured and calculated by SCD100 and KT Analyzer by KLA-Tencor. S621D can achieve 1.2 nm inter-field and 2.1 nm intra-field CDU.

The Critical Dimension (CD), which is often the width of features on the wafers, affects device performance by changing the resistance and capacitance of the semiconductor devices. Maintaining high device yields requires good control of CDU within each chip and across the wafer.

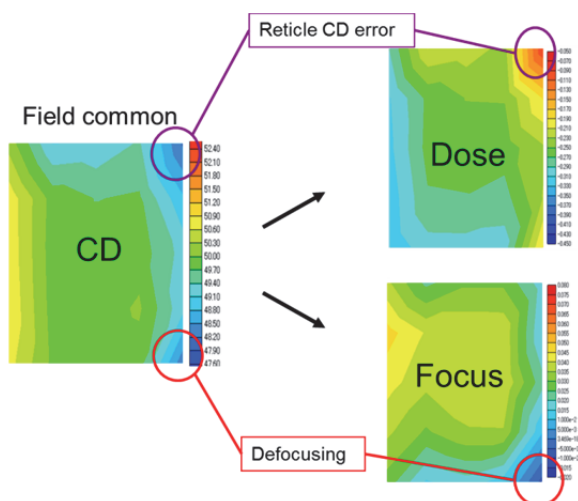


FIGURE 6. Intra-field error components from the data in Figure 5.

As shown in Figure 5, CDU measurements are classified into inter-field and intra-field components. Different controls within the lithography machine are used to compensate for

both types of variation. Software tools can automatically determine which adjustments are necessary to compensate the measured intra-field and inter-field “fingerprints” of the exposure machine and reticle. The intra-field corrections, including illumination dose and focus from the data in Figure 5 are shown in Figure 6. After applying the corrections from Figure 6, the CDU of the entire wafer is improved to well below 1 nm 3-sigma, as shown in Figure 7. To enable these corrections, many features need to be designed into the lithography tool to provide the necessary degrees of freedom. For example, dose is controlled using components in the illumination system, varying the excimer laser output, and adjusting the trajectory of the reticle and wafer.

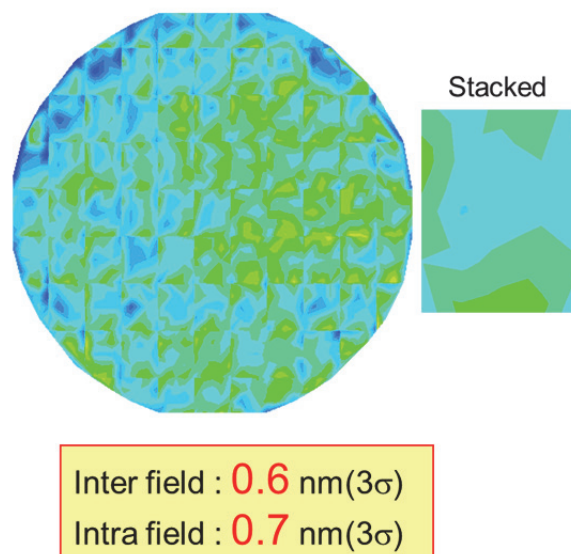


FIGURE 7. Measured CDU after applying intra-field corrections. Compared to the data in Figure 5, the common intra-field “fingerprint” of each die has been removed.

FOCUS

Focus performance of S621D is shown in Figure 8. These data are determined by measuring focus-sensitive features on the exposed wafer. Achieving 12.2 nm, 3-sigma, focus accuracy requires careful engineering and control in several areas:

- The wafer needs to be securely chucked to a stable wafer holder. The wafer holder needs to maintain nanometer-level stability, which requires careful consideration of thermal stability, thermal deformation,

dynamic deformation during acceleration, and careful selection of materials.

- The on-machine autofocus system must be able to accurately measure the wafer topography. Each wafer is covered by a stack of thin layers, each with their own patterns. Accurate and high-speed measurement of these surfaces is challenging.
- The stage positioning control needs to position the wafer properly in all 6 DOF while it is executing a complicated trajectory with large accelerations.
- The body of the machine must hold the optics in a stable position. Temperature and vibration control of the projection lens is critical.

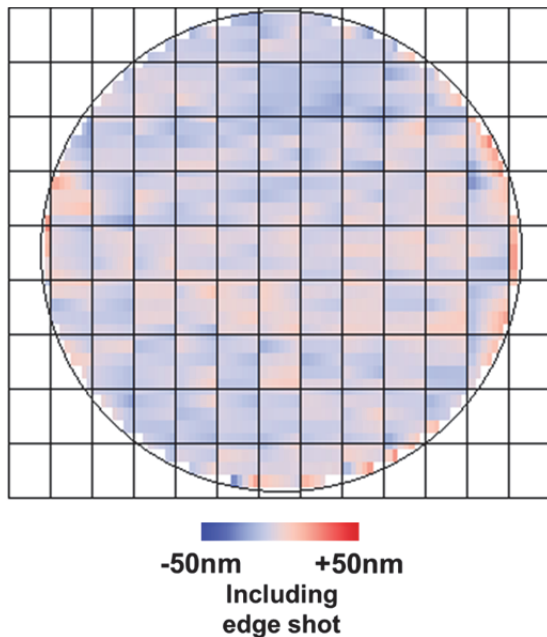


FIGURE 8. S621D Focus Uniformity measurement of 12.2 nm, 3 sigma.

OVERLAY

One of the most challenging performance requirements for a modern lithography scanner is overlay. The standard reticle size is a 150 mm square. Modern wafers are 300 mm diameter. Both of these objects need to be precisely positioned and controlled during exposure. The lithography machine needs to be engineered to ensure that there are no unknown or non-repeatable nanometer-scale deformations or distortions of either the reticle or wafer. For a 500 mm square wafer table and a 2 nm overlay target, these requirements mean

the stability and positioning accuracy of every point on the top surface needs to be

$$\frac{2 \text{ nm}}{500 \text{ mm}} = 4 \text{ ppb.}$$

Meeting this target requires significant engineering effort in several areas:

- Thermal disturbances. The actuators, typically brushless linear motors, dissipate kilowatts of heat. The lithography machine is full of small lasers, optical components, sensors, and circuit boards which are all heat sources. The reticle, wafer, and precision optical components need to be carefully isolated from these heat sources.
- Thermal deformation. Careful selection of materials, precise temperature control, and proper use of kinematic constraint is necessary to avoid thermal deformation of critical components.
- Vibration control. The wafer and reticle stages need to be stiff and have high vibration mode frequencies that will not be excited by the stage trajectory. Reaction forces need to be absorbed in a manner that does not cause disturbances or vibrations.
- Near-perfect repeatability. For the stage control system to properly compensate any positioning errors or mechanical deformation, the operation of the stages needs to be nearly perfectly repeatable and deterministic. Hysteretic or nonlinear components, such as hoses and cables to the moving stages, can easily cause non-repeatable overlay errors. The electronics and control system need to maintain accurate timing of sensor and actuator signals.

Recent overlay results from S621D are shown in Figure 9. These data show consistent performance better than 2 nm for mean+3 sigma overlay in both the X and Y directions. The first plot shows overlay measurements on one wafer. The second and third plots show consistent performance across a lot of 25 wafers.

Meeting this target of <2 nm overlay requires developing an overlay error budget which contains many terms, such as:

- Reticle distortion
- Reticle stage positioning error
- Changes in the projection lens distortion
- Wafer distortion
- Wafer stage positioning error

- Micro-slip or hysteresis of the wafer or reticle deformation
- Wafer stage to reticle stage alignment error
- Wafer alignment measurement error

Clearly, to provide a total overlay error under 2 nm, each of these error sources must be controlled to a fraction of a nanometer.

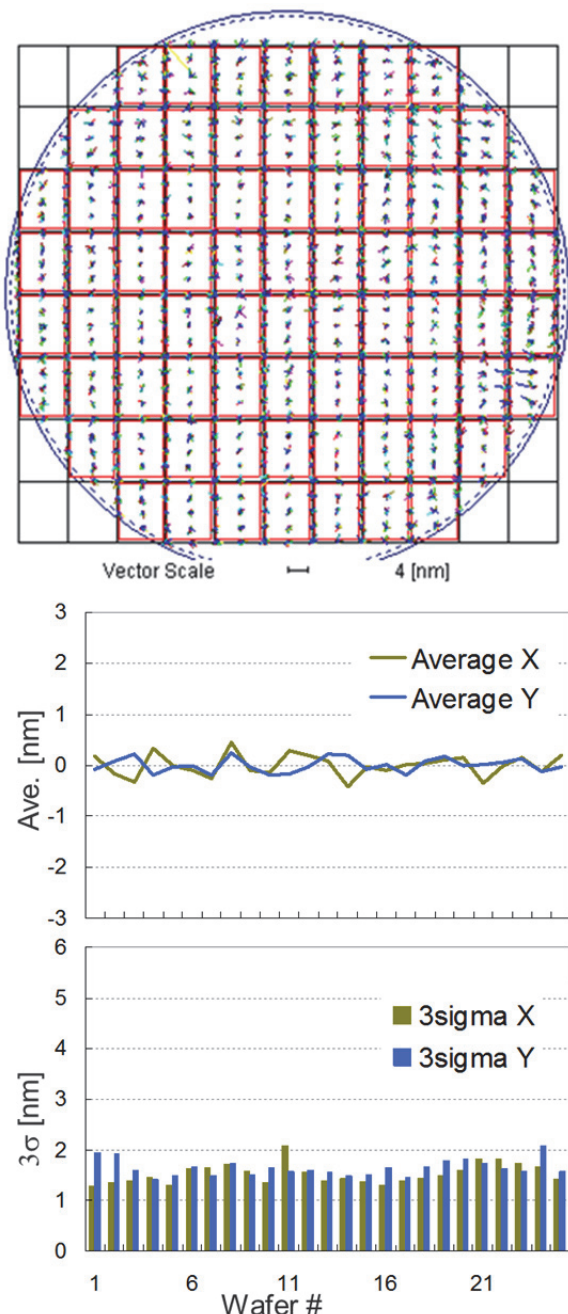


FIGURE 9. S621D Single Machine Overlay performance. Average + 3sigma: 1.86 nm X, 1.89 nm Y.

Modern lithography machines like S621D include many features to correct individual components of the overlay error budget. Figure 10 illustrates active reticle bending, which is provided on S621D. By using non-kinematic constraints and actuator forces, it is possible to apply a bending moment to the reticle stage about the Y (scanning) axis, which projects into the page in the schematic at the top of Figure 9. Since the reticle pattern is on the bottom surface of the reticle, reticle bending can stretch or compress the pattern to reduce overlay errors. The data plotted in the lower half of Figure 9 show good linearity in the correction.

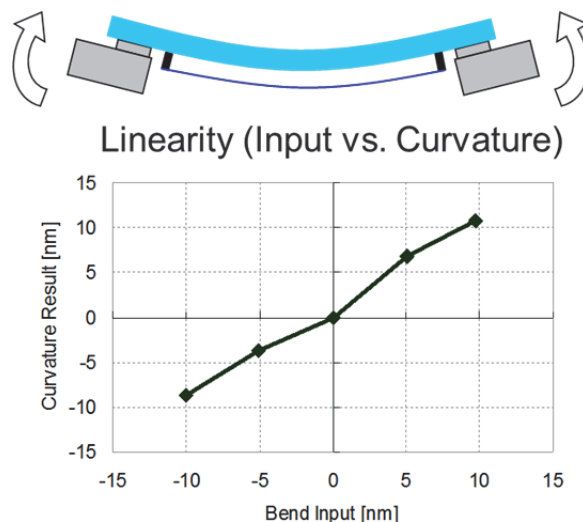


FIGURE 10. Overlay errors caused by reticle shape variations and gravity sag can be corrected by bending the reticle stage. The top figure shows an end-view of the reticle stage. The light blue reticle is bent about the Y (scanning) axis. The plot shows good linearity in the overlay correction.

Figure 11 shows the “5-Eye” Field Image Alignment (FIA) alignment system of S621D. The positions of alignment marks on the wafer are measured by five microscope objectives. Using five sensors simultaneously allows measurement of more alignment sites on the wafer to improve overlay performance, without sacrificing throughput. Maintaining alignment and calibration of the five eyes relative to each other requires sophisticated sensors, mechanical design, and system engineering.

S621D uses an encoder system to measure the wafer stage location using four grating plates on the perimeter of the Wafer Table. These grating

plates are shown in Figure 11 as yellow rectangles on the perimeter of the wafer table. The grating plates on S621D use an improved mechanical structure, which provides better stability than Nikon's previous machine, S620D. The improvement is shown in Figure 12, where the 2-week stability of the grating plates is improved from 8.3 to 2.9 mm and from 3.2 to 1.6 m for X and Y, respectively.

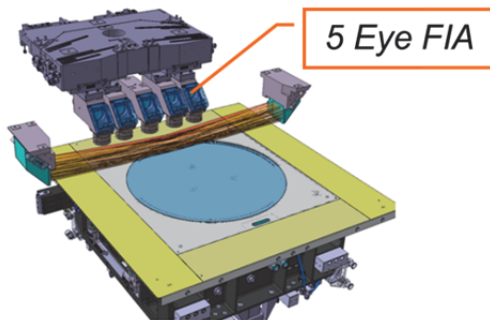


FIGURE 11. The S621D alignment system uses five alignment microscopes (FIA) to measure the location of alignment marks on the wafer.

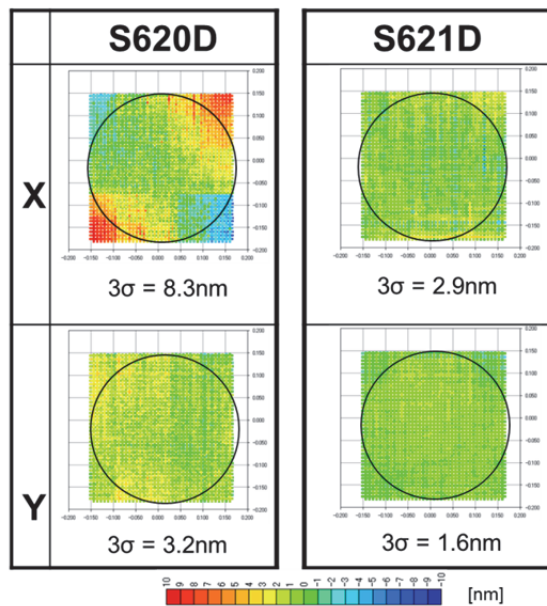


FIGURE 12. Grating plate stability improvement from S620D (left) to S621D (right). A new mechanical structure for the grating plates provides significant overlay improvement.

One additional illustration of the difficulty of meeting modern overlay targets is that the relative position of the wafer and reticle stages must be adjusted to account for the time-of-flight

for the exposure light to travel from the reticle to the wafer, a distance of about 1.6 m.

THROUGHPUT

While maintaining nanometer overlay and imaging performance, modern lithography machines also need to be exceedingly fast. As shown in Table 1, S621D achieves wafer throughput of 200 wafers/hour (wph). This performance means each wafer is in the tool for less than 18 seconds. During this time, many operations are performed:

- pre-alignment
- loading on the wafer chuck
- FIA alignment measurement
- autofocus measurement
- alignment of the wafer to the reticle
- exposure of approximately 100 shots
- unloading

Exposure occurs while the reticle and wafer stages are both scanning at high velocity in the Y direction. Between each exposure shot, both stages need to change direction, requiring a large Y acceleration. In addition, the wafer stage must step to the next exposure site in the X direction.

TABLE 1. Throughput performance of S621D with 2 standard shot maps.

Shot Map	Throughput
125 shot, 16x32 mm	200.3 wph
96 shots, 26x33 mm	220.5 wph

Meeting the Throughput specification requires scanning (exposure) and stepping (acceleration) times on the order of 50 msec, each. There is zero settling time between acceleration and exposure, so there can be no non-repeatable residual vibration or deformation at the instant acceleration is finished. Making this process work requires sophisticated mechanical design, control system design and tuning, and careful design and shaping of the acceleration trajectory.

PRODUCTIVITY

Building a lithography tool that meets these difficult performance targets is challenging. For cost-effective high volume manufacturing, however, the customers require machines that achieve this performance reliably and consistently. Figure 13 shows the potential productivity of S621D, maintaining 213 wph average throughput for 24 hours to process

5112 wafers/day (wpd). The “real world” productivity goal of S621D is 4000 wpd.

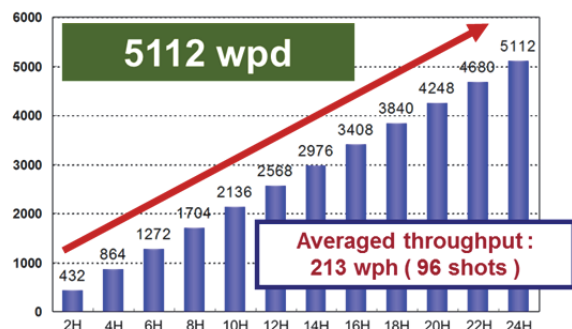


FIGURE 13. Productivity potential of S621D in a 24 hour test.

CONCLUSIONS: FUTURE DEVELOPMENT

Modern lithography tools can achieve imaging, overlay, throughput, and productivity targets that seem almost impossible. Constant application of Precision Engineering principles are necessary to meet the performance targets. Every component needs to be carefully selected and calibrated to provide repeatable and linear behavior. The lithography system must be designed to ensure near-perfect repeatability and deterministic behavior of each element. Careful attention must be directed to thermal effects, kinematic support, materials selection, and vibration characteristics. Balancing the engineering tradeoffs and paying sufficient attention to all of these details make lithography tool design an exciting and challenging field.

Figure 14 shows the recent history of the lithography industry. Alternatives to extend optical lithography, such as High Index immersion (to increase NA above 1.35) and F2 lasers (to reduce the exposure wavelength to 157 nm) have been canceled. EUVL, with a wavelength of 13.5 nm is under development, but is not yet ready for commercial application. For now, the industry is using Double Patterning (DP) technology to extend ArF immersion to smaller feature sizes. The downside of DP techniques is increased complexity and cost. As indicated above, this trend will likely continue with extensions to Triple or Quadruple Patterning, which will further increase processing cost.

There are several significant challenges that are delaying the commercial introduction of EUVL:

- Light-source power is not yet sufficient to enable high throughput production.
- There are still problems with reticle fabrication and defect correction.
- The sensitivity of EUV photoresist is not yet able to meet the requirements of volume production.

As these challenges delay EUVL, the industry continues marching to Moore’s Law, so the requirements are constantly growing more difficult and the projected cost of EUV lithography is rising.

Moore’s Law can be expressed in many ways, such as transistor count, memory density, or CPU performance. The fundamental metric that drives the industry, however, is the cost per transistor. As lithography becomes more expensive, the industry is looking more seriously to 450 mm wafers as a way to maintain a steady cost/transistor improvement. Since many wafer processing steps can be performed on a full wafer, or a batch of wafers simultaneously, larger wafers reduce the fabrication cost of semiconductors. 450 mm wafers will improve the economics of semiconductor manufacturing, but will require significant improvements in the design and operation of lithography tools.

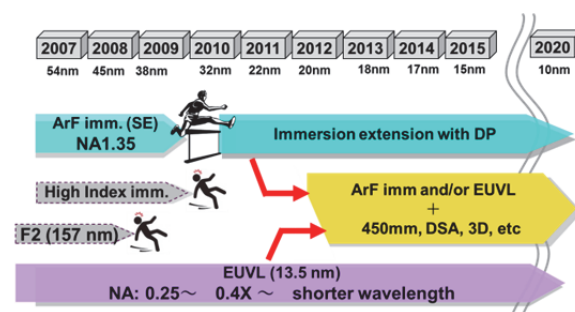


FIGURE 14. Recent history of lithography development. Feature half-pitch for each year is from the ITRS 2010-2011 roadmap for flash memory.

Most likely, the industry will adopt a combination (shown in yellow in Figure 14) of ArF immersion and other technologies, such as EUVL, Directed Self Assembly (DSA), 3D semiconductors, and 450 mm wafers to extend lithography towards 10nm hp around the year 2020 and smaller features beyond that. Although state-of-the-art lithography has reached many of the “fundamental physical limitations,” clever engineers and scientists will find ways to

continue the technological improvement of the semiconductor industry. We are not running out of Precision Engineering problems to solve.

REFERENCES

- [1] Uehara Y, Shibasaki Y, Ishikawa J, Kohno H, Tanaka E, Masanori O. Immersion and Dry ArF Scanners Enabling 22nm HP Production and Beyond. SPIE Advanced Lithography 2012. Paper 8326-53.
- [2] Matsuyama T, Kita N, Ikeda J. Application of Illumination Pupilgram Control Method with Freeform Illumination. SPIE Advanced Lithography 2012. Paper 8326-20.
- [3] Fujiwara T, Toki T, Tanaka D, Sato M, Kosugi J, Tanaka R, Sakasai N, Ohashi T, BNakasone R, Tokui A. Process Window Control Using CDU Master. SPIE Advanced Lithography 2012. Paper 8326-26.
- [4] Matsuyama T, Mizumo Y, Ohmura Y, Ogata T. Imaging Optics Setup and Optimization on scanner for SMO Generation Process. SPIE Advanced Lithography 2012. Paper 8326-23.
- [5] Shiba Y, Makino K, Morita Y, Motoyoshi C, Yamamoto H, Udagawa J, Kikuchi T, Shirata Y, Ishii Y. High Overlay Accuracy for Double Patterning Using an Immersion Scanner. SPIE Advanced Lithography 2012. Paper 8326-29.

Linear stage and metrology architecture for Reflective Electron Beam Lithography (REBL).

Upendra Ummethala¹, Layton Hale¹, Josh Clyne¹, Samir Nayfeh¹, Mark Williams¹, Joe Diregolo¹, Anne van Lievenooen², Jerome van Loo²

¹REBL Division
KLA-Tencor Corporation
Milpitas, CA, USA
²Philips Innovation Services
Eindhoven, The Netherlands

Abstract:

This paper describes the design of a stage and metrology system for use in a Reflective Electron Beam Lithography (REBL) application. REBL is a novel concept for high speed mask-less projection electron beam lithography, funded under a cost-shared joint KLA-Tencor and DARPA contract, targeting high volume wafer fabrication at 16 nm half pitch resolution. REBL uses a DPG (Digital pattern Generator) chip with > 1 million pixels to modulate an electron aerial image while reflecting it toward the wafer, where it is de-magnified to produce a high resolution pattern.

Previously, REBL has been using a rotary stage to perform lithography, the details of which have been disclosed in a prior ASPE conference. We are now designing a linear stage capable of holding multiple wafers, which will simplify the data-path while maintaining high throughput. This paper describes the key features of this stage and metrology system.

The wafer stage comprises of a pair of magnetically levitated stages that move in the scan direction at high linear speeds of up to 1m/s. The pair of maglev stages provide a means of canceling reaction

forces without the need for counter moving sacrificial masses. The maglev stage pair moves on a conventional bearing stage that provides motions in the slow step direction. The two stages share a common vacuum, the details of the configuration of this system will be detailed in the paper.

A novel interferometer based metrology system is being designed to measure the positions of the moving maglev stages in all six degrees of freedom. Additional wafer and beam metrology systems are being designed in order to facilitate accurate measurement of both the wafer distortions as well as the location of the electron beam while writing the wafer. The novel scheme adds minimal overhead to perform these alignment tasks.

Additionally, the stages feature very precise thermal control of several components of the stage system that allow the system to meet the stringent Overlay and CDU requirements needed from this high throughput direct write electron beam tool. The electromagnetic design of the maglev stages as well as other material selection is made to minimize the effect of the stages on the electron beam.

PLASMONIC IMAGING LITHOGRAPHY MACHINE (PILM)

Mohamed E. Saad, Robert J. Hocken
Center for Precision Metrology,
University of North Carolina at Charlotte,
Charlotte, NC, USA

The goal of the current research project is to design, manufacture, assemble and calibrate a state of the art plasmonic imaging lithography machine. This project is a result of the cooperation between the "Center for Precision Metrology" (CPM) located at University of North Carolina at Charlotte and the Center for Scalable and Integrated NanoManufacturing (SINAM) located at University of California at Berkeley.

1. INTRODUCTION:

The lithography can be done using many techniques such as Photolithography (optical, UV, EUV), E-beam/ion-beam lithography, X-ray lithography, Interference lithograph and Nanoimprint. Imprint lithography and optical lithography are highly attractive due to the high throughput for mass fabrication. Also, photolithography has been a major fabrication method in the integrated circuit (IC) and semiconductor industries over the past several decades. Nanoimprint lithography has demonstrated great capabilities, however, the leveling of the imprint template and the substrate during the printing process is a challenge.

Deep UV photolithography can offer a resolution of sub-100 nm; but the spacing between patterns and the minimum feature size are determined by the diffraction limit of light [2]. In order to overcome the diffraction limit some technologies were developed such as near field interference lithography and phaseshifting mask lithography [2].

There are some critical concerns when generating subwavelength features from apertures smaller than the exposing wavelength such as low transmission through the apertures, poor contrast and limitation of the exposing distance [2].

2. PLASMONIC IMAGING LITHOGRAPHY (PIL)

Surface Plasmons are fluctuations in the electron density at the material boundaries and can strongly couple with photons. With this effect, some metal structure can "focus" light into a nano-spot in near-field. This structure is called Plasmonic Lens (PL) [3].

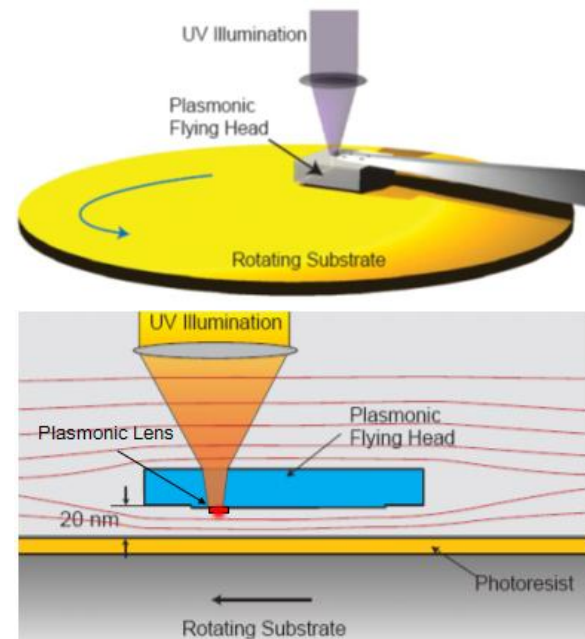


Figure1. Illustration of Plasmonic Lithography [3]

Plasmonic Imaging Lithography (PIL) has many advantages such as being high resolution, maskless, Lower cost, and high speed technique. Also, the PIL is highly flexible, user friendly, and has the potential to achieve throughputs that are two to five orders of magnitude higher than other maskless techniques.

3. PLASMONIC IMAGING LITHOGRAPHY MACHINE (PILM) DESIGN

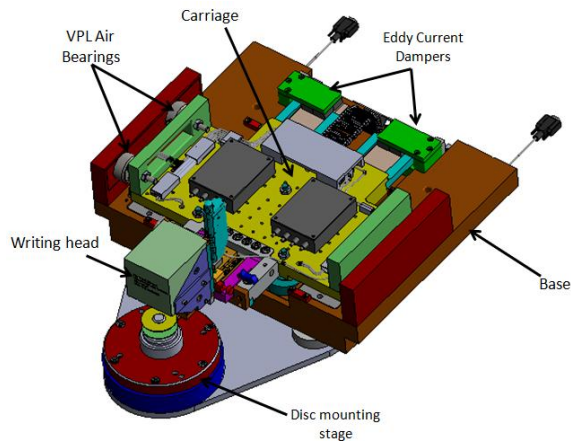


Figure 2. Plasmonic Imaging Lithography Machine (PILM)

The machine composed of an aluminum base which stands on 3 leveling feet. The disc is mounted on 1000-3000 RPM rotary stage in order to provide a compensation for thermal expansion, an aluminum base plate has been designed where the disc mounting stage and the front two leveling feet will rest on.

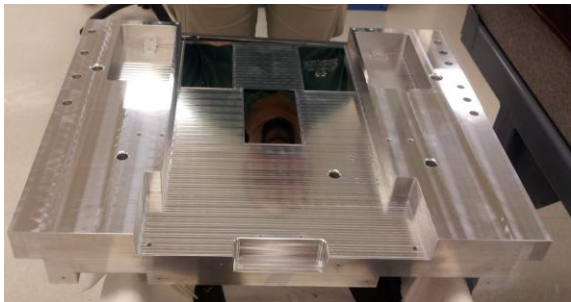


Figure 3. PILM's base.

The carriage is made of AL 6061, and to provide a frictionless motion, three Vacuum Preload (VPL) airbearings are carrying the carriage weight. The linear motion needed to move the carriage is provided by a two three-phase Helbach linear motors. The Helbach array motor provides an accurate and smooth motion that can be controlled. The Helbach linear motor generates force in both longitudinal and vertical directions. Each motor composes of a 24-coils stator and an eight-magnets Helbach array.

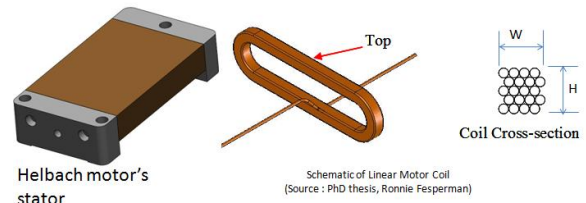


Figure 4. Illustration of the stator design of Helbach linear motor.

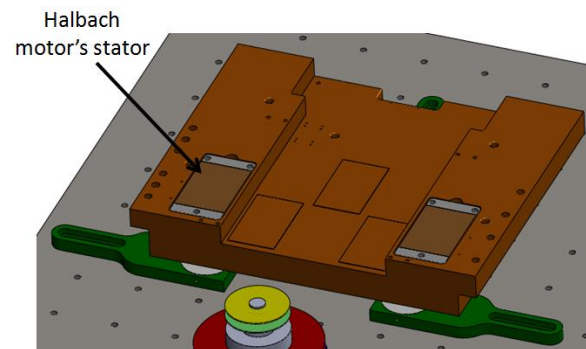


Figure 5. Illustration of the stators locations on the PILM base.

In order to achieve the required accuracy, two 5-nanometer linear scales has been attached to the carriage. The read heads are mounted on the base, and the readings of these nano-precision scales can be used to determine the carriage position and to determine the actual linear speed. Also, the difference between the two readings can be used to determine any yaw that may happen during the linear motion and based on that a correction feedback signal will be generated.

Also, damping has been introduced to the system to provide a smooth linear motion. Eddy Current Dampers (ECD) have been designed and manufactured. The ECD composes of a copper plate that moves in between a magnet array composed of eight magnets. The yoke that holds the magnet array will be attached to the base and the copper plate will be attached to the carriage using an aluminum bracket. The carriage average linear speed is $5 \mu\text{m/s}$, and at this speed the ECDs will generate 0.01N damping force.

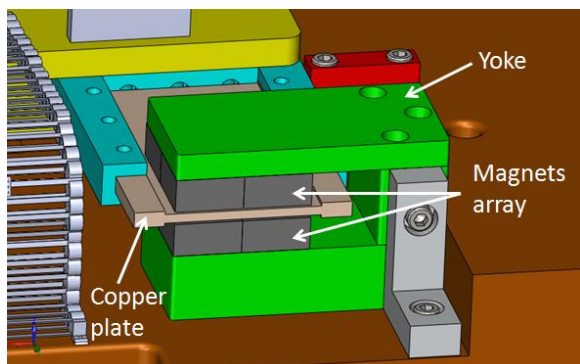


Figure 6. Illustration of the Eddy Current Damper (ECD) deisng.

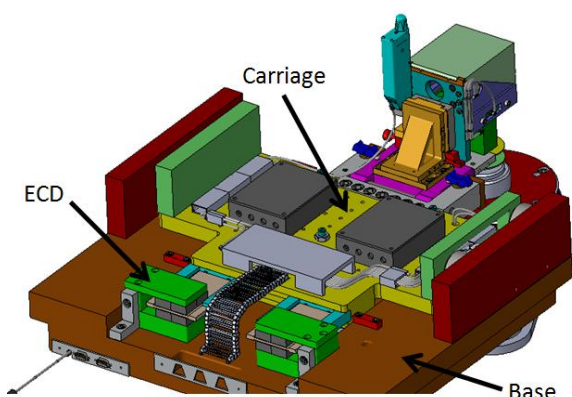


Figure 7. Illustration of the ECD locations on the PILM.

The writing head is composed of a main slider, two brackets that hold the prefocusing stage, suspension bracket and the White Light Interferometer (WLI) bracket.

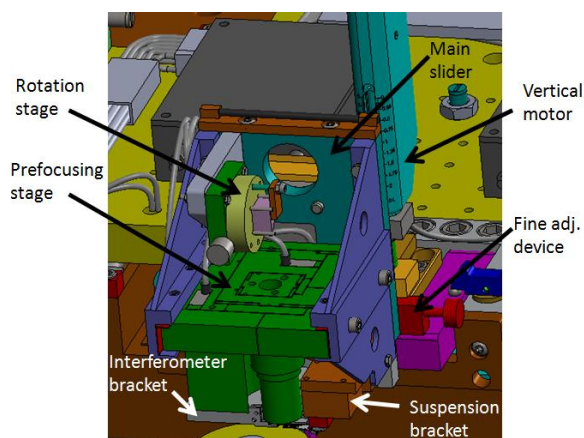


Figure 8. Illustration of the writing head components.

Also, the main slider is equipped with a 2" linear motor that provide a vertical motion of the writing

head during the plasmonic lens changing procedure. Also, the slider is resting on a fine adjustment device which is attached to a rotation arm that will provide a 90° rotation needed during the PL changing procedure.

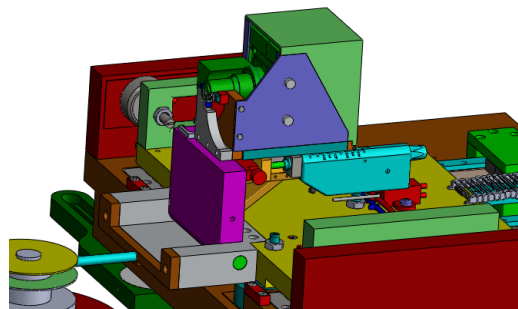


Figure 9. Illustration of the writing head rotation during the PL changing procedure.

The PL can move in the radial (downtrack) and tangential (off track) directions using piezoelectric shear actuator of 3μm range in both directions. Also, the machine is equipped with a White Light Interferometer (WLI) attached to the writing head. Christopher Hughes designed the WLI bracket and he is working on the interferometer design. Christopher uses two needles as fiber optics holders and directed the laser beams to mirrors attached to the slider sides. After measuring the vibration, a feedback signal will be generated and applied on a two dimensional shear actuator to make any required correction.

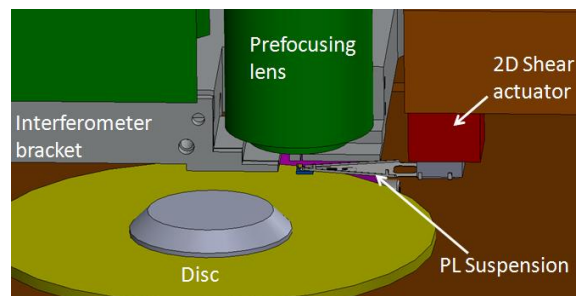


Figure 10. Illustration of the PL and the shear actuator locations.

And to provide the required prefocusing of the UV beam, a prefocusing stage has been designed by Dr. Wen Wang. The prefocusing stage provides three dimensional motion of the prefocusing lens for a 50x50x100 μm range. Also, the writing head is equipped with a rotation stage to direct the UV beam to the prefocusing lens.

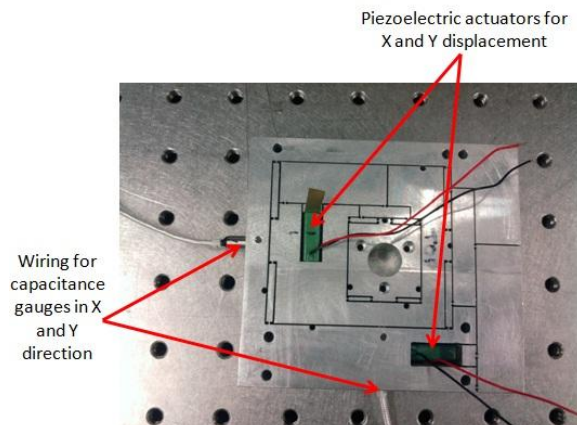


Figure 11. The prefocusing flexure designed by Dr. Wen Wang.

4. THE PILM SPECIFICATIONS:

The PILM is designed to produce 45 nm line width at 45 nm half pitch. The overlay (3σ) is expected to be 11 nm (1/4 of pixel size). The following figure illustrates the machine coordinate system.

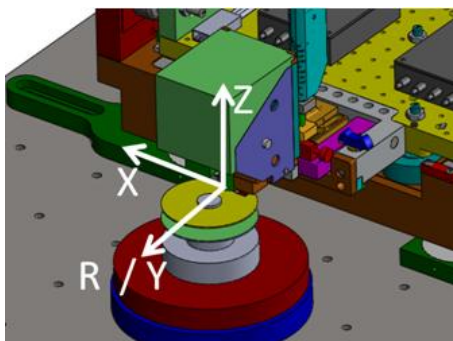


Figure 12. Coordinate system on the PILM

The PL maximum travel range is (2.26") 57.40 mm in the radial direction, this will allow for future developments of the machine. Currently, the requirement is set to be only (1.5") 38.1 mm travel length.

A tabulated list of the PILM performance specifications is shown below.

Table 1. PILM Performance Specifications.

Maximum Radial (Downtrack) Travel	57.40 mm (2.26")
Radial Travel	38.1mm (1.5")
Radial Position Error	5 nm
Radial Resolution	< 5 nm

Radial Minimum Speed	100 nm/s
Radial Average Speed	5 $\mu\text{m/sec}$
Pixel Size	45 nm
Accuracy	5 nm
Prefocusing Stage range	X and Y :50 μm Z :100 μm
Disk spinning speed limits	1000-1500 RPM
Average Writing time (full disk)	5 hrs
PL Lifetime (pre-alignment)	2 min
PL Lifetime (post-alignment)	20 min
Carriage Angular Stiffness	75 N/ $\mu\text{-rad}$
Carriage Linear (lateral) stiffness	26 N/ μm
Carriage Linear (vertical) stiffness	39 N/ μm
θ_x Leveling Error	1 $\mu\text{-rad}$
Z-axis Fine Motion Travel	6mm
Z-axis Coarse Travel (Vertical motor)	50.8 mm (2")
Alignment Time	1 min

5. FUTURE WORK:

The machine parts have been designed and analyzed statically and dynamically using a design software package. Many elements have been manufactured and the machine is currently in the assembly stage. After assembly, the machine will be tested and calibrated and any necessary adjustments will be made, then the machine will be shipped to SINAM's lab at the University of California at Berkeley.

REFERENCES

- [1] Stephen Y. Chou, Peter R. Krauss, and Preston J. Renstrom. Nanoimprint lithography, J. Vac. Sci. Technol. B 14(6), Nov/Dec 1996
- [2] Werayut Srituravanich, Nicholas Fang, Cheng Sun, Qi Luo, and Xiang Zhang ,

Plasmonic Nanolithography, *Nano Letters*,
4 (6), pp 1085–1088, 2004

- [3] Werayut Srituravanich, Liang Pan, Yuan Wang, Cheng Sun, David B. Bogy, and Xiang Zhang. Flying plasmonic lens in the near field for high-speed nanolithography, *Nature Nanotechnology*, VOL 3, DEC. 2008

Status of Jet and Flash Imprint Lithography Steppers for Sub-25nm Semiconductor Memory Manufacturing

Babak Mokaberi[†], Pawan Nimmakayala[†], Zhengmao Ye[†], Philip Schumaker[†],
Jin Choi[†], Dwayne LaBrake[†], S.V. Sreenivasan^{†,‡,§}

[†] Molecular Imprints, Inc. [‡] University of Texas at Austin

[§] Corresponding Author, sv.sreeni@mail.utexas.edu

1.0 INTRODUCTION

Jet and Flash Imprint Lithography (J-FILTM) has demonstrated remarkable replication capability down to sub-10nm resolution. Translating this nano-scale resolution to a commercially viable manufacturing approach requires addressing key challenges in tools, materials, masks (templates) and processes that can achieve reliable nano-scale performance at reasonable cost. This article focuses on the stepper tool and presents two key aspects of tool hardware and the associated imprinting process. These aspects are building blocks for high resolution overlay capable tools for sub-25nm half-pitch memory manufacturing using the J-FIL technology. First, a design of an 8 channel opto-mechanical system that provides real-time feedback of alignment data is presented along with its design specifications and image processing capability.. Next, a step and repeat imprinting process is presented that produces clearly defined boundary of each field and also eliminates any open space between adjacent fields on 300mm wafers. The adaptation of J-FIL for semiconductor manufacturing requires this as it is essential to create a contiguous patterned resist on silicon wafers to avoid etch and CMP loading challenges.

A discussion of other J-FIL technology related results including etch and CD control, defectivity and throughput is provided in recent articles^{1,2,3,4}.

2.0 ALIGNMENT FEEDBACK SYSTEM

In optical scanning lithography tools, multiple alignment feedback data are collected through the large projection lens system, which provides unobstructed beam path. To increase yield and also throughput, global alignment schemes have been adapted as the main methodology on most scanning projection tools. In J-FIL systems, the implementation of a global interferometric measurement system is complicated by the fact that there is a possibility that the wafer and template may undergo nano-

scale slipping on the their respective chucks during the patterning steps. In current J-FIL steppers, a through the template alignment measurement scheme have been adopted where alignment targets in the template and wafer are captured when the two targets are in proximity. This approach can be used instead of or in conjunction with a global alignment approach. In this paper, alignment refers to the accuracy of an imprinted field registered relative to a wafer field, at the alignment targets, while overlay refers to full-field registration. An example alignment approach uses two alignment data sets per corner of the patterned fields. Since all alignment data collection and corrections are performed in parallel to fluid filling, use of field-to-field real-time alignment scheme does not limit throughput of the process³.

2.1 Alignment Mechanism

Fig. 1 illustrates a dual-channel alignment mechanism that is based on the Interferometric Moiré Alignment Technique (IMAT) developed originally for X-ray lithography^{5,6}. At each field a total of 8 IMAT cameras are pointed toward the alignment marks (one camera per mark). Since each camera provides one-axis alignment measurement, four sets of (dx, dy) alignment data can be collected and these 8 degree of freedom (dof) data per-field can be used to compensate for rigid body errors X, Y and rotation and non-rigid body errors in mag_X and mag_Y, orthogonality, and X and Y trapezoidal errors^{7,8}. Additional discussions about the 1st order Moiré schemes in imprint lithography are available in the literature⁹. An actuation system and algorithm to vary template dimensions to handle non-rigid body template corrections were previously presented in the literature⁸.

Alignment data collection at ~50Hz and real-time error compensation is performed continuously as the drop-dispensed gap between the template and wafer changes from in-proximity to partial fluid filling, and finally, full fluid filling just prior to the UV exposure step.

Micron-level errors are quickly compensated when template and wafer are brought in proximity. More precise error correction is performed as fluid spreading progresses from the center of the field. Finally, the fine errors are corrected when the resist is still in liquid form before the UV curing step where in addition to the X, Y and θ components, magnification, orthogonality and trapezoidal errors, are compensated. During the development of the alignment mechanism, following process requirements and specifications were pursued to satisfy real-time data capturing in parallel to fluid filling process steps:

1. Resolution of <1nm
2. Eight channel data capturing at >50Hz/ch
3. No optical obstruction to the UV exposure and full-field imaging for *in-situ* process diagnostics.
4. Fast reconfiguration (<500msec) of the alignment mechanism to varying field geometry for partial fields located near the wafer edge.

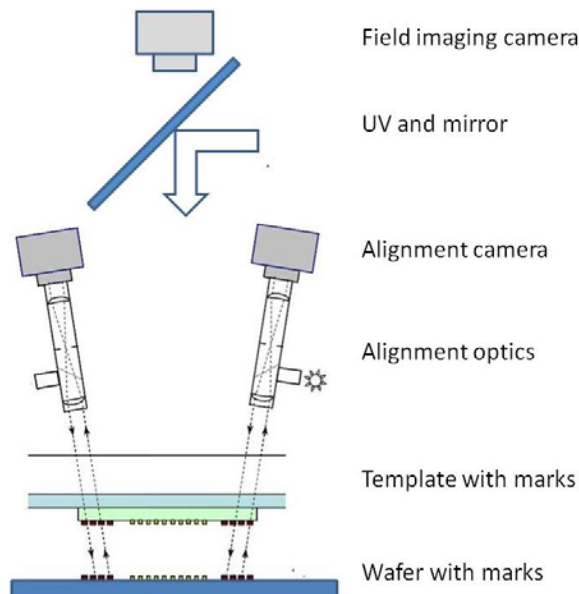


Fig. 1 Optical system layout with dual-channel alignment mechanism, a field imaging camera and UV mirror (not in scale).

Specification 4 is required to maximize the wafer device yield wherein partial fields at the edge of the wafer need to be patterned. Fig. 2 illustrates a partial field layout that includes a 2x4 device array. The arc shows the wafer edge and the fact that only two of the eight devices are completely on the wafer. In this case six of the eight alignment microscopes need to be

moved in to capture the intra-field alignment marks at the edge of the rectangle that encompasses the two yielding devices.

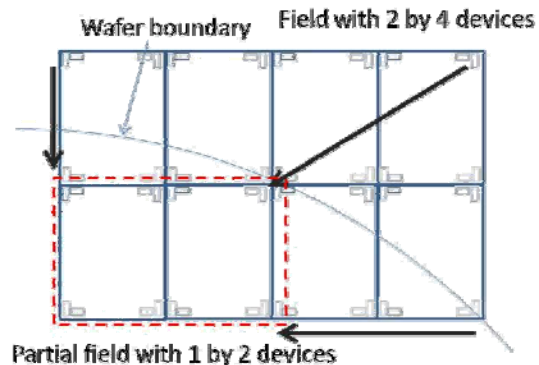


Fig. 2 Bottom left 1 by 2 are yielding devices for this partial field

Packaging eight optical and CCD units along with the precision stages needed to reconfigure the alignment system for edge fields within a limited space was a challenging engineering task. Four design parameters were used to select optical microscope units; angle of inclination, optical resolution, objective lens diameter, and working distance. Using partial scanning CCD cameras with frame rates of >150Hz, and sophisticated image processing algorithms, the alignment errors of the order of one nanometer can be measured⁷. The microscope units have a 110mm working distance and their relative small diameter of 16mm was suitable to provide sufficient open space above the template. A top view and a local cross-section of the 8-channel iMAT system are shown in Fig. 3. Each set of microscope and CCD camera is mounted on a focusing and X-Y stages.

2.2 iMAT Stage Step and Settling Performance

Dynamic performance of the assembled i-MAT system was evaluated for all eight channels with repeated step and settling tests. The bulky cable systems for the camera and stages acted as external disturbances. System integration was focused on the bottom Y-stage since it supports additional payload of the X-stage. Small linear stages with a motion range of (+/-) 20mm were customized with appropriate linear motors and absolute linear encoders. Fig. 4 shows step and settling motion of the Y stage. Settling within 10nm was achieved within 400msec and repeated motions showed a repeatability of ~40nm in 3 sigma. This level of

dynamic performance and precision is sufficient for the reconfigurability of the i-MAT system. As far as the alignment marks are in the field of view, absolute location of the microscope does not affect the alignment measurement for iMAT.

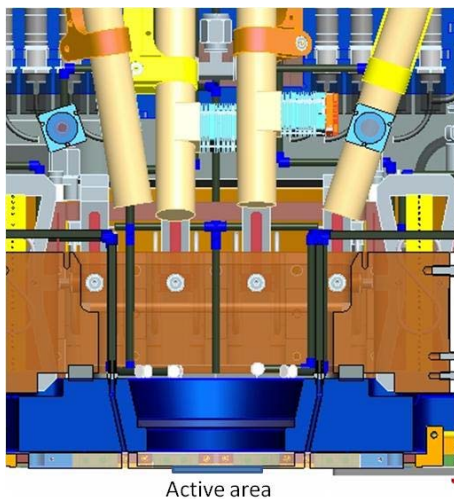
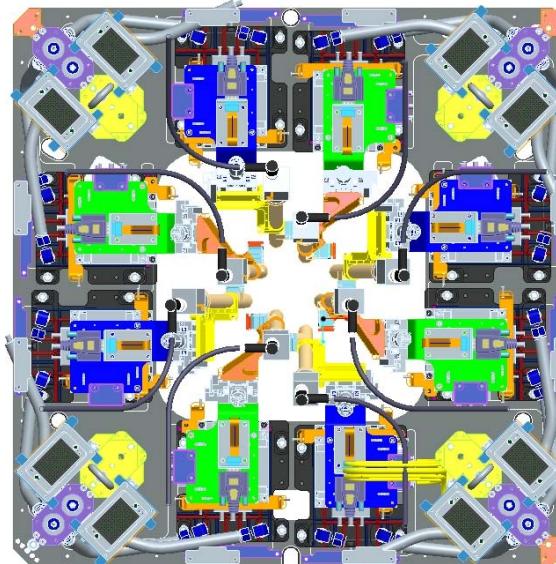
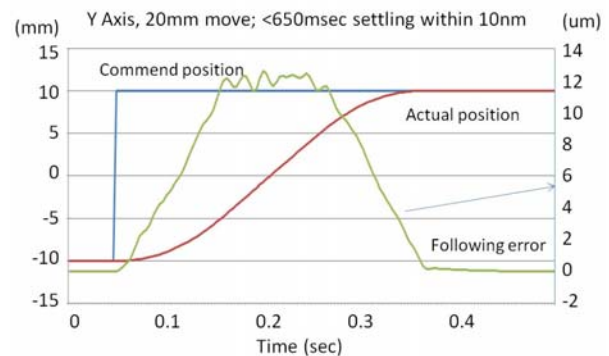


Fig. 3 Top view of eight-channel iMAT and cross-section images of microscope with the template active area

2.3 Overlay Performance

With the 8-channel iMAT, alignment and overlay data was gathered for five consecutive wafers. Layer 1 (underlying layer) was generated with a ASML1950i photo scanner, and layer 2 was patterned using a J-FIL stepper. Table 1 shows overlay results where multiple overlay data were measured within each field. Overall vector plot for the last wafer is shown in Fig. 5.



Y Stage Repeatability	Spec (mm)	3 sigma (mm)
Positive Stroke	+/- 0.008	4.10837E-05
Negative Stroke	+/- 0.008	4.54556E-05

Fig. 4 Step and settling of Y-axis over 20mm and repeatability data

	X Mean	Y Mean	X 3σ	Y 3σ	X m+3σ	Y m+3σ
Wafer A	-0.1	+1.3	13.2	15.1	13.3	16.4
Wafer B	-0.6	-0.3	13.4	13.7	14.0	14.0
Wafer C	-0.4	-0.4	13.8	13.5	14.2	13.9
Wafer D	-0.3	0.1	12.9	12.7	13.2	12.8
Wafer E	-0.6	-0.1	11.8	12.1	12.4	12.2

Table 1 Overlay data for 5 wafers (nm)

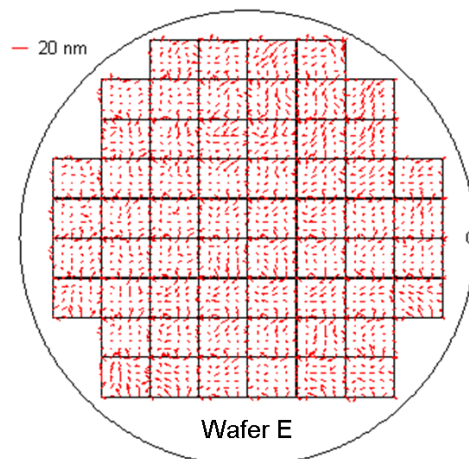


Fig. 5 Overlay vector plot for 5th wafer.

3.0 IMPRINT FIELD WITHOUT OPEN SPACE

J-FIL technology can be used to pattern full substrates. However, since semiconductor memory lithography requires nano-scale overlay, J-FIL patterning has to be performed in a step and repeat manner. The field size of 26mm x 33mm is chosen to enable mix-and-match overlay with photolithography.

Step and repeat J-FIL patterning on 300mm silicon wafers requires patterning one rectangular field at a time, with each field receiving its resist deposition just prior to the patterning and UV exposure of that field. This is needed to ensure that the evaporation of the wet resist (in liquid form) does not compromise the resist formulation and therefore the process quality. In addition, stray UV light can cure adjacent fields if the resist has been dispensed on multiple field.

The above process leads to a key challenge. The boundaries of each rectangular field has to be clearly defined and any large open spaces between adjacent fields should be eliminated. Open spaces will cause etch and CMP loading, which directly affects the device yield. Therefore, all partial fields need to be imprinted, and imprinted fields need to have zero gap between them to eliminate the open spaces. In order to achieve this process specification, boundary of each imprinted field needs to be accurately defined as a copy of the sharp boundary of the glass template active area.

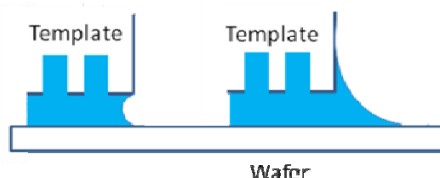


Fig. 6 Balanced fluid boundary (left), unbalanced fluid boundary with fluid leaking out

As shown in Fig. 6, in order to define the boundary cleanly, it is important to balance the imprinting force and also drop volume/position so that fluid drops do not escape from the small gap between the template and wafer. When drop position control in proximity with the boundary is not properly achieved, it will cause either excessive fluid outside of the field or under-filled regions. Errors in template placement relative to the fluid drops dispensed can cause one side of field with fluid leaks and the opposite side with fluid starvation.

3.1 Fluid Control

Since fluid drops are in circular shape and field boundary is in straight line, spreading fluid layer will not reach all boundaries at the same time. Therefore, it is important to relieve any compressive force between the template and wafer as the fluid drops reach the boundary and allow capillary pressure between two surfaces complete the remaining fluid filling so that

boundary can be clearly defined. This problem is more sensitive especially at four corners where two boundary lines meet.

High speed drop on demand dispensing is essential for semiconductor memory fabrication with J-FIL. To minimize dispensing time, a constant speed of 500mm/s dispensing speed is used and drop position accuracy of better than 10microns is achieved.

3.2 Imprint Boundary Control

The ideal case of boundary control is a clean and straight field definition. If a previous imprinted field has fluid layer extended beyond its boundary, the next imprinting field will have non-uniform residual layer thickness. The non-uniform thickness will cause either CD error or feature loss.

As shown in Fig. 6, the J-FIL resist materials are designed to have a wetting interface with the template and the wafer surfaces. The resist is more wetting with the wafer than it is with the template to provide a differential adhesion during the separation step. The wetting interface with the template along with a well defined template edge creates a capillary pinning effect provided the resist dispense location and template position is controlled carefully as discussed earlier. This pinning effect provides an interval of time over which the wetting liquid turns the sharp template corner prior to wetting the vertical wall of the template. This pinning provides a short time, of the order of 1 or 2 seconds, when the liquid is confined and can be captured with the UV exposure step. This approach has been successfully implemented to create a robust process performance. Fig.7 shows corner images where four fields meet demonstrating the boundary control and the ability to create a contiguous patterned resist film on silicon wafers.

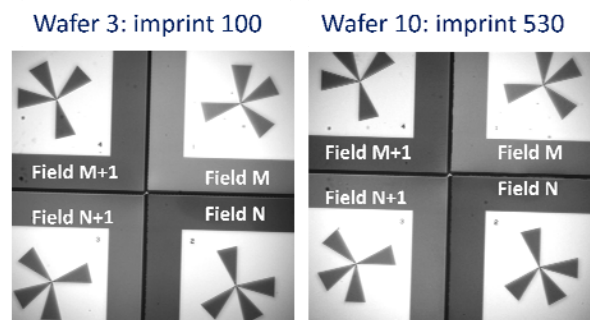


Fig. 7 Images of four fields with clean boundary and no open space

4.0 SUMMARY

Two challenging topics for semiconductor memory fabrication with J-FIL processes were presented. The multi-channel opto-mechanical alignment system to support high resolution overlay and a novel process to eliminate any open spaces between adjacent clearly provide building blocks for practical implementation of J-FIL process in semiconductor device fabrication. A discussion of other J-FIL technology related results including etch and CD control, defectivity and throughput is provided in other recent articles.

ACKNOWLEDGEMENTS

This research work was partially funded by the Texas Emerging Technology Funds program.

REFERENCES

- ¹ S.V. Sreenivasan, B.J. Choi, P.D. Schumaker, F. Xu, " Status of UV Imprint Lithography for Nanoscale Manufacturing," Comprehensive Nanoscience and Technology, 2011, Vol. 4, 83-116.
- ² Z. Ye, K. Luo, X. Lu, B. Fletcher, W. Liu, F. Xu, D. LaBrake, D. J. Resnick, S. V. Sreenivasan, "Imprint Defect Analysis for Semiconductor Memory Applications Using Jet and Flash Imprint Lithography," Under Review, SPIE Journal of Micro/Nanolithography.
- ³ Sreenivasan, S.V. et al., "Critical dimension control, overlay, and throughput budgets in UV nanoimprint stepper technology," Proceedings of the ASPE 2008 Spring Topical Meeting, April 2008.
- ⁴ C. Mark Melliard-Smith, "Lithography Beyond 32 nm: A Role for Imprint?" Proceedings of SPIE Advanced Lithography, Key Note Presentation, Vol. 6517 p. 21, 2007.
- ⁵ Moon, E.E. et al., "Application of interferometric broadband imaging alignment on an experimental x-ray stepper," Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, November 1998, 16(6), p. 3631.
- ⁶ Moon, E.E. et al, "Interferometric-spatial-phase imaging for six-axis mask control", J. of Vacuum Science and Tech. B, 21(6), pp. 3112-3115, 2003.
- ⁷ Choi, B.J. et al., "Distortion and overlay performance of UV step and repeat imprint lithography," Microelectronic Engineering, 2004 V78-79, p633, January 2005.
- ⁸ Cherala, A., et al., "An Apparatus for Varying the Dimensions of a Substrate During Nano-Scale Manufacturing," US Patent No. 7,170,589.
- ⁹ Li et al, "Sub-20-nm Alignment in Nanoimprint Lithography Using Moiré Fringe", Nano Letter, 6 (11), 2626 -2629, 2006.

Recent Advancements in Long-Travel, Nanoscale Optic/Substrate Positioning with Quantitative Measurement of Long-Term Stability

Scott C. Jordan
Director, NanoAutomation Technologies
PI (Physik Instrumente) L.P.
San Jose, CA, USA

ABSTRACT

Moore's Law has driven relentlessly tightening requirements for positional resolution in optic and substrate positioning in semiconductor microlithography and metrology applications. This trend has been accompanied by commensurate needs for positional stability. For example, significant technological development and facilities investment has been devoted to devising and deploying vibration isolation technologies that shield sensitive equipment from environmental perturbations such as seismic disturbances from machinery and personnel. Similarly, stage brakes and clamping air-bearings have also proven valuable for improving the stability of certain automated assemblies.

All these benefit nano-sensitive applications in many ways, ultimately in terms of yield and throughput. But another, insidious instability process can also bedevil sensitive applications: quasi-asymptotic, nanoscale settling due to lubricant flow processes in drive, alignment and adjustment elements such as leadscrews and micrometers. This is slow, progressing at the nanoscale over many minutes. Since conventional position-metrology instrumentation is typically less stable than recent process tolerances over the timescales involved, quantification of these issues has been lacking.

Here we review:

- An emerging class of motion drive technologies capable of nanoscale resolutions over long travels, including in challenging environments (ultra-clean, high vacuum, fieldless/non-magnetic, and/or EUV);
- A novel metrology approach which allowed, for the first time, comparative quantification of long-term, nanoscale drift/settling behaviors at the nanoscale, and
- A family of actuation mechanisms that mitigates drift issues by eliminating their source.

BACKGROUND

The stability of an apparatus can be no better than the stability of each of its subassemblies. Gradual drift/settling behavior, commencing with motion and perhaps varying in time or with conditions, is particularly problematic to performance, yield and throughput. Some contributors have been analyzed thoroughly in the literature; for example, the dimensional stabilities of structural materials are well established [1].

One contributor that has been analyzed on a material level is the lubricant in the screw mechanism of spindle-driven stages. The lubricant flows and displaces into an eventual equilibrium state. The rheology of lubricants such as greases commonly used in screw actuation mechanisms has been studied extensively, yielding classical models such as the straightforward Bingham Model, supplanted over the years with more elaborate understanding [2] and analyzed experimentally as a function of time in the transition from the dynamic to a quasi-static regime [3].

Unfortunately, understanding of this behavior has remained theoretical due to the instability of conventional position-metrology equipment at the nanoscale over the relevant timescales. It is evident, though, that eliminating such lubricant films in drive mechanisms would improve long-term stability. Applying a stage brake might be another possibility, but these inevitably disturb the position of the mechanism when actuated, and their effectiveness on the nanoscale is unproven for the same reason of inadequately stable metrology over the long term. Replacing the screw with a magnetic linear motor or voice coil would be no answer since those mechanisms hold position by consuming current, contributing to thermal drift and "hunting" behavior by the servo.

EMERGING PIEZO-BASED, LONG-TRAVEL TECHNOLOGIES PROVIDE SELF-LOCKING

Familiar piezo stack actuators, commonly used in nanopositioning components, are composed of layers of ceramic interleaved with electrodes; applied voltages produce controllable dimensional changes which are useful for responsive nanoscale actuation of mechanisms. However, the maximum expansion of these actuators is about 0.1% of their length. Flexure amplifiers have been employed for up to 2 mm of actuation from a stack only a few dozen mm long. Longer travels have traditionally necessitated magnetic motors of various sorts.

That changed with the past few years' innovations in long-travel, direct-drive piezo-ceramic motors. Quite different from stack actuators, these fall into three basic categories, all capable of many centimeters of travel: *walking*, *stick-slip* and *ultrasonic*. Importantly, some configurations engage the ceramic directly with the moving workpiece, such as in the case of an ultrasonic motor whose oscillating frictive tip is preloaded against a drive-strip on the workpiece or the example of a walking actuator whose motive elements are preloaded against a drive shaft. In both cases the screw's lubricant film is eliminated. (Other piezomotor implementations actuate a rotating screw and thus do not eliminate the drift processes under discussion.)

In one family of unlimited-travel technologies based on piezo ceramics that includes resonant [4] and non-resonant [5] approaches, one or more ceramic forcers are preloaded against a ceramic-surfaced stage platen or actuator shaft so that their actuation may confer motion. In some variants, actuation characteristics are similar to a familiar DC servomotor's, in which the velocity is approximately proportional to the magnitude of the applied stimulus. In all cases, the actuation mechanism provides inherent braking force when stimulation is ceased—the mechanisms essentially form a ceramic stage brake.

A direct benefit of these long-travel piezomotors, then, should be improved in-position stability. This has been believed to be the case even down to the nanoscale, although metrology challenges have until recently denied quantitative demonstration.

Resonant Piezomotors

In a specific example of this breed of piezomotors (FIGURE 1), a ceramic wafer is configured so that high-frequency excitation of one of a pair of stimulating electrodes drives one or more resonant modes in its material, conferring a small oscillatory motion to the friction pusher tip affixed at a vibrational antinode for the resonance, typically on the midline of one long side of the ceramic slab. The tip, oscillating like a miniature pogo-stick with nanoscale amplitudes and frequencies of hundreds of kHz, can then be preloaded against a guided workpiece, driving long-travel motion. Actuation speed is approximately proportional to the amplitude of the stimulation, as with a DC servomotor, though (again in analogy to a pogo-stick) a threshold stimulation is required before motion occurs. This deadband behavior is valuable for eliminating hunting behavior by the servo.

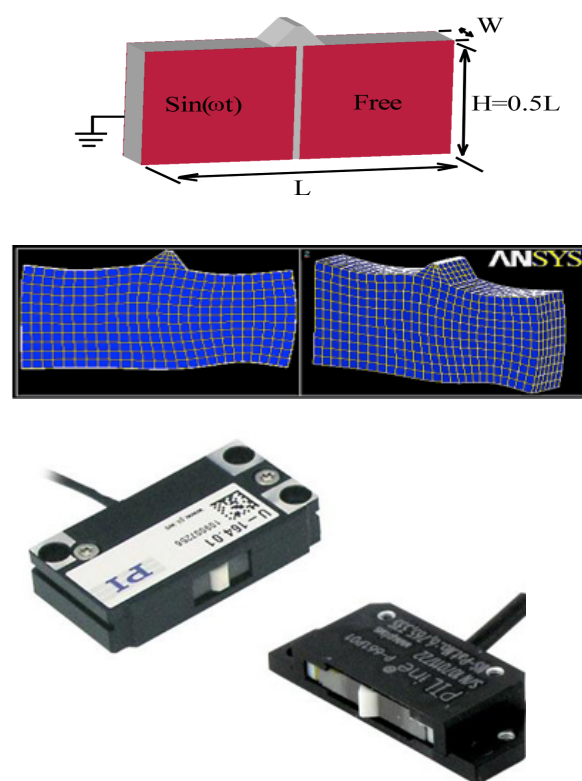


FIGURE 1. Novel resonant piezomotor places a frictive actuating tip at the vibrational antinode of a piezoceramic slab. When preloaded against a workpiece, ultrasonic stimulation of the slab confers motion. When quiescent, it acts as a ceramic stage brake, improving system stability.

By eliminating lead-screws and their inertia and associated linkages and structures, such mechanisms can be very compact and responsive. For example, off-the-shelf linear stages can provide 19mm of travel at up to 500mm/sec and 10gee acceleration with a 0.1 μ m resolution linear encoder, all in a package 35mm square. Even smaller mechanisms have been devised, such as a miniature self-guided piezomotor actuator for miniature camera, fluid delivery and endoscopy applications.

In addition to in-position stability superior to that of conventional stages, other signature advantages of piezo actuation apply such as fieldlessness, vacuum-compatibility, EUV compatibility, and long life.

Piezo Walking Drives

By combining piezo elements acting in longitudinal and transverse directions, the foundation for a walking actuator is composed. These elements can be compressed against a longitudinal rod to confer motion. One familiar progenitor of this family of mechanisms was the Burleigh Inchworm, no longer manufactured. More recently-developed mechanisms offer extraordinary stiffness and holding force and are optimized for reliability in applications requiring long-term position hold while providing centimeters of travel with picometer-class resolution.

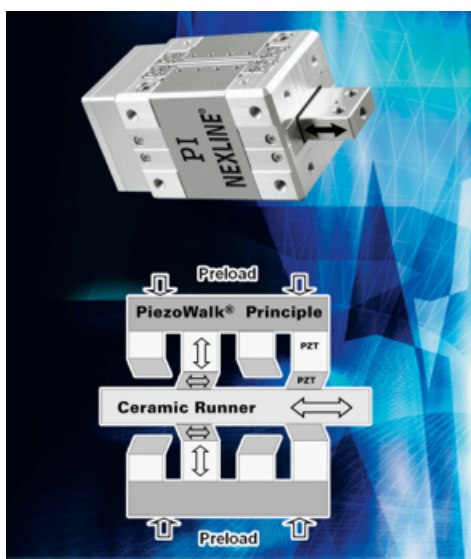


FIGURE 2. Walking motors represent another class of long-travel piezomotors. Composed of forcer elements which directly confer incrementing and fine slew motions to a ceramic

runner, these mechanisms provide cm-scale travel, picometer resolution, long-term position-hold with power off, and actuation forces into hundreds of Newtons.

An even newer solution uses cost-effective bender-type piezo elements. Size and cost are substantially reduced; power-off stiffness is still remarkable, with 10N holding force. This design also provides centimeters of travel range and picometer-class positionability, ideal for applications like optic positioning and sample positioning in e-beam direct-write applications (FIGURE 3).

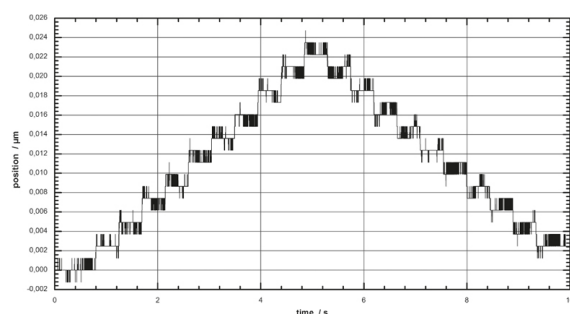


FIGURE 3. Integration of an 0.5nm-resolution encoder in a walking-type piezomotor-driven stage yields these 2nm commanded steps.

In the case of both these walking-style piezomotor types, motion occurs in two modes: a long-travel stepping mode, and a fine-motion analog mode in which the actuator elements are sheared, providing sub-nm positioning capability.

QUANTIFICATION OF LONG-TERM, NANOSCALE POSITION STABILITY

While the stability benefits of piezomotor actuation has been conjectured for decades, documenting stability quantitatively at the nanoscale over long periods has remained an elusive goal. For example, conventional optical position-metrology interferometers have typically lacked the necessary long-term stability to provide quantitative measurement of structural stabilities over periods of many minutes.

Recently, researchers in the field of single-molecule biophysics have utilized optical tweezers in a configuration that quantitatively compared the stabilities of screw-driven and piezomotor-driven stages with sub-nanometer sensitivity over many minutes [6]. As in many semiconductor-industry applications, the test

setup stacks coarse-positioning (resolution 0.1 micron) and fine-positioning motion elements (resolution 0.1 nanometer) in a sophisticated microscopy configuration. Traditionally in this field the coarse-positioning substage has been a screw-driven mechanism, but piezomotor-based microscopy stages have recently been commercialized. By swapping the coarse-positioning stage between screw-driven and piezomotor-driven models, the long-term, nanoscale stability provided by the piezomotors was quantitatively revealed.

The stability of each substage was measured on a dual-beam optical trapping microscope. 600nm-diameter polystyrene beads were adhered to a glass coverslip and mounted on the nanopositioning stage carried by the stacked X-Y substages. The beads' positions were measured by back-focal plane detection [7] using a laser imaged onto a position-sensitive diode (PSD); the combination of clever optics and processing of the PSD signals provided sub-nanoscale localization of the bead in three dimensions. The position of the beads was tracked at five minute intervals, allowing compilation of the long-term overall system drift trends shown in FIGURE 4. The incremental stability provided by elimination of the screw-driven coarse-positioning mechanisms is evident. While long anticipated, such validation of piezomotors' long-term stabilities had not been quantitatively visualized before.

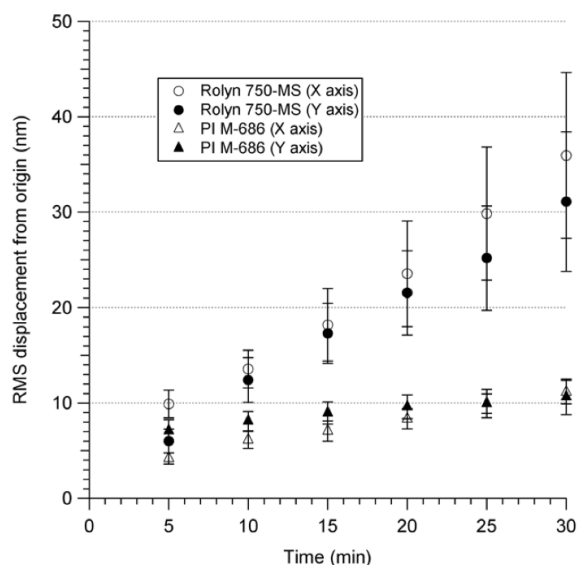


FIGURE 4. From [7], a novel application of optical tweezers allowed long-term, nanoscale quantification of overall system drift in a microscopy configuration including either a

screw-driven coarse-positioning stage or a piezomotor-driven equivalent. As can be seen here, elimination of the actuating screw and its lubricant interface results in significantly improved long-term nanoscale stability.

NEXT: A NEW FRONTIER IN DIMENSIONAL PICOMETROLOGY

Meanwhile the capability of next-generation optical interferometers continues to advance. A key requirement for their industrial deployment is concomitant development of sufficiently accurate metrology and dimensional standards for verification of these next-generation instrumentation and tools. Extraordinary progress has very recently been made in the field of highly accurate dimensional nanometrology by leveraging x-ray diffractive interferometry with recently-developed digital controls approaches. Work performed at European sites including England's National Physical Laboratory have utilized user-programmable FPGA architectures and a novel DAC resolution enhancement technique contributed by the author to servo-control a piezo-driven, monolithic silicon x-ray interferometer, locking it on the diffractive fringe structures. Since the crystallographic lattice structure of silicon is well understood, this approach yields quantized steps of picoscale absolute accuracy. These researchers' demonstration of subatomic absolute accuracies has very recently been published [8]. These instruments are targeted to validate the performance of next generation displacement measuring optical interferometers within the European Metrology Research Program's project NANOTRACE.

APPLICATIONS

Mechanisms potentially benefiting from this capability for long travel with nanoscale resolution and long-term, nanoscale stability range from microlithographic staging and fixture positioning systems to piezomotor variants of classical optic and substrate positioners. The all-ceramic drive principle is amenable to EUV applications and has been implemented in a novel, six-degree-of-freedom, UHV, fieldless, ultra-stable compact hexapod for critical EUV front-end applications.

REFERENCES

- [1] Slocum, A.H. (1992) Precision Machine Design, Society of Mechanical Engineers, Michigan, p. 335.

- [2] Hutton, E.g., J.F. (1975) On using the Weissenberg rheogoniometer to measure normal stresses in lubricating greases as examples of materials which have a yield stress. *Rheol. Acta*, 14, 979-992.
- [3] Madieto, E.g., J.M.; Franco, J.M.; Valencia, C. and Gallegos, C. (2000) Modeling of the non-linear rheological behavior of a lubricating grease at low-shear rates. *J. Tribol.*, 122 (3), 590.
- [4] Spanner, K. (2006) Survey of the various operating principles of ultrasonic piezomotors, in *Actuator Bremen*, June 2006.
- [5] Marth, H. and Lula, B. (2006) Development of a compact, high load PZT-ceramic, long-travel, linear actuator with picometer resolution for active optical alignment applications. *Proceedings of the SPIE*, Vol. 6273, p. 62731K.
- [6] Jordan, S. and Anthony, P. (2009), Design Considerations for Micro- and Nanopositioning: Leveraging the Latest for Biophysical Applications, *Curr. Pharm. Biotechnology*, 2009, 10, 515-521
- [7] Neuman, K.C. and Block S.M. (2004) Optical trapping. *Rev Sci Instrum.*, **75** (9), 2787-2809.
- [8] Çelik1, M., Hamid, R., Kuetgens, U. and Yacoot, A., Picometre displacement measurements using a differential Fabry–Perot optical interferometer and an x-ray interferometer, *Meas. Sci. Technol.* **23** (2012) 085901, online at <http://iopscience.iop.org/0957-0233/23/8/085901/>

CONCEPTUAL DESIGN OF MECHATRONIC MACHINE COMPONENTS USING TOPOLOGY OPTIMIZATION

Kostiantyn Vandyshev, Matthijs Langelaar, Fred van Keulen and Jan van Eijk
Department of Precision and Microsystems Engineering
Faculty of Mechanical, Maritime and Materials Engineering
Delft University of Technology
The Netherlands

MOTIVATION

After years of discussions, the transition to 450mm wafers in semiconductor industry now looks inevitable. With these larger wafers the production efficiency increases by means of more efficient wafer material use and less wafer exchange time.

On the other hand, simply scaling up the existing systems, which are able to carry a wafer of 300 mm, by a factor 1.5 will roughly increase the mass by more than a factor 3. Assuming that performance of the system remains the same, we conclude that actuators should be scaled up to provide bigger control effort. This also means that the actuators will be heavier and provide more energy dissipation and heat production, which degrade the performance of the entire system. Thus, straightforward scaling of the machine elements is not an appropriate method for design and, consequently, another approach should be developed.

An additional disadvantage of bigger machine components is the decrease of the natural eigenfrequencies, which makes control properties worse. This abstract discusses topology optimization to arrive at mechanical designs with improved mechanical performance.

CONCEPT OF TOPOLOGY OPTIMIZATION

Methods of shape and size optimization work by means of changing a small number of parameters, while designs remain conceptually the same. In contrast, topology optimization [1] searches for an optimal design within a given design domain, subject to certain prescribed design requirements, boundary conditions and applied loads. The obtained design meets these requirements and maximizes the performance. Important is, in comparison to shape and size optimization, that topology optimization allows more design freedom and may result in unexpected but well-performing solutions. This method may im-

prove the traditional mechatronic design strategy, which first optimizes the structural design and then the control system [2]. Structural optimization for eigenfrequency maximization is a typical problem in the abovementioned application. In this work we evaluate this method for a moving component of a mechatronic system, so low mass and high eigenfrequencies are essential for a good system performance.

Topology optimization for eigenvalue problems has been already studied well, see e.g. [3] for a recent overview of work done in this field. We consider a generalized eigenvalue problem:

$$(K - \lambda_j M) \phi_j = 0 \quad (1)$$

$$\phi_j^T M \phi_k = \delta_{jk}, \quad (2)$$

where M and K are symmetric and positive definite mass and stiffness matrices respectively, λ_j is j th eigenvalue and ϕ_j is the corresponding eigenvector. The design or material layout is described by local density design variables ρ_e , which affect K and M directly. The topology optimization process iteratively determines optimal values of these local densities. It is known that the sensitivity of the eigenvalue to a particular design variable ρ_e can be described by the following formula:

$$\frac{\partial \lambda_j}{\partial \rho_e} = \frac{\phi_j \left(\frac{\partial K}{\partial \rho_e} - \lambda_j \frac{\partial M}{\partial \rho_e} \right) \phi_j}{\phi_j^T M \phi_j}. \quad (3)$$

Therefore, an effective optimization algorithm for eigenfrequency maximization can be set up.

DESCRIPTION OF OPTIMIZATION PROBLEM

In this paper, we apply topology optimization on a design problem depicted in Fig.1, discretized by 120x60x30 fixed regular elements. The material is aluminum with Young's modulus $E = 70$ GPa, Poisson's ratio $\nu = 0.3$ and mass density $\rho = 2700$ kg/m³. This simplified model represents a moving component of a mechatronic machine, where low

mass and high eigenfrequencies are crucial characteristics for a good system performance. The purpose of this component is to carry some load or another part of machine on its surface, therefore the upper layer must not disappear during topology optimization.

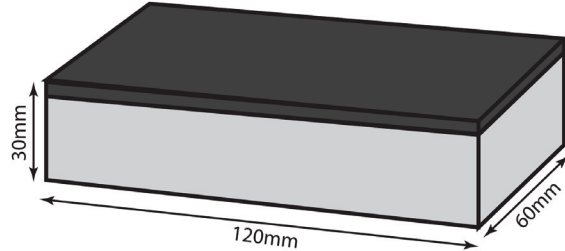


FIGURE 1. Initial design for topology optimization. The light grey domain can be changed during optimization.

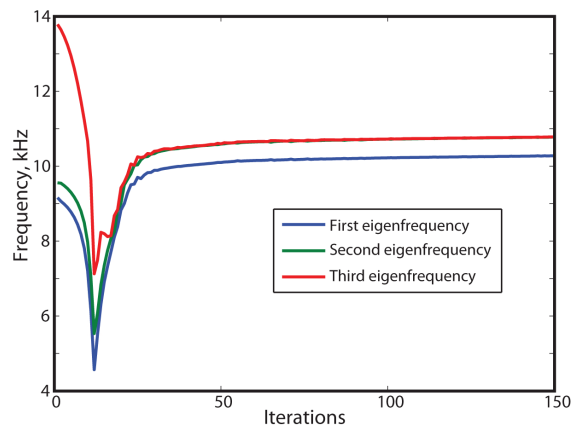


FIGURE 2. Evaluation of the three lowest eigenvalues during optimization process.

The goal of optimization is to maximize the lowest eigenfrequency of the structure, so higher bandwidth controllers can be implemented. Practically, maximization of the first eigenfrequency without consideration of the second one will result in the coalescence of the first two eigenfrequencies, which results in modeswitching and usually causes instability of optimization process. Therefore we use a condition to keep the second eigenfreq at or above 110% of the first eigenfreq, e.g. a 10% distance constraint. Another constraint which is used in the optimization formulation is a volume fraction restriction, which is typical of topology optimization formulation.

Our topology optimization algorithm is based on SIMP (Solid Isotropic Material with Penalisation)

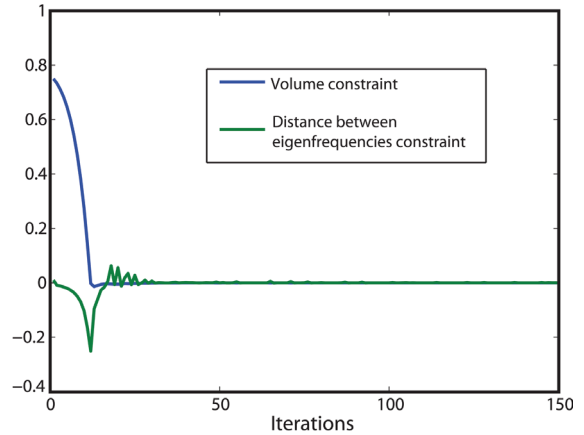


FIGURE 3. Evaluation of the constraints during the optimization process.

method [1] implementation enhanced with density filtering [4] and MMA (Method of Moving Asymptotes) optimizer [5].

RESULTS

To gain an insight in the optimization procedure we analyze one particular problem in detail. Consider the optimization domain depicted in Fig.1 with 10% distance constraint between first and the second eigenfrequency and a 50% volume fraction restriction. The iteration history of the objective function is shown in Fig.2. The optimization process was stopped after 150 iterations, when the relative change of the objective function did not exceed the value of 10^{-5} . The process starts with a full solid block, so the initial eigenvalues correspond to that. It can be seen that the lowest eigenfrequency increases with 12% percent. From Fig. 2 and also from Fig. 3, which shows the constraints evaluation during the optimization process, we conclude that 50 iteration is decent bound for future optimization cycles. Fig. 4 and Fig. 5 visualize the outcome of the topology optimization process. Fig. 6 shows two sections of the obtained optimal design in order to show the shape of the inner cavity. Fig.7 shows the eigenshapes of the structure.

Although it may seem impractical to fabricate this relatively complex structure, note that results of topology optimization are typically used for guidance in the conceptual design phase. Moreover, with increasing capabilities of additive manufacturing technologies, we expect that it will soon become practical to fabricate complex components such as this directly, thus avoiding any design

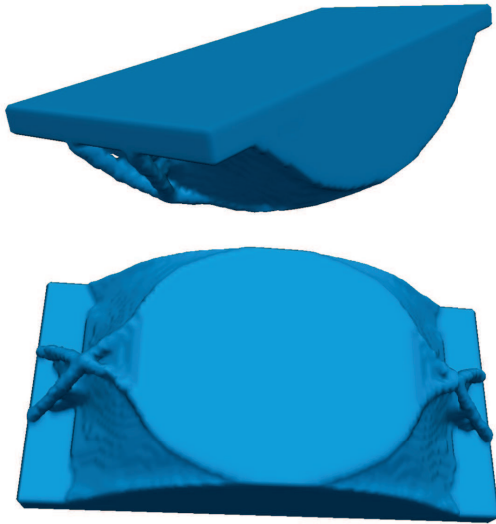


FIGURE 4. Surface appearance of the obtained design. Top view (upper) and bottom view (down).



FIGURE 5. Top view through the transparent structure of the obtained design.

compromises for manufacturability.

Higher volume fractions allow the optimization process to use more material and therefore the inner cavity becomes smaller, and minor structural details gradually disappear, however the cavity itself remains. Fig. 8 shows the lowest eigenfrequencies of the obtained optimal designs for different volume fractions. It is seen that the best values are obtained at the higher volume fractions, because in this case the optimizer has more material placement freedom. It was found that optimizer does not use more than 88% of the volume even if a larger amount of material is allowed. This type of graph may also be used to find the best tradeoff between mass and eigenfrequency in a mechatronic system, as lowering the mass results in lower eigenfrequencies but still may result in an overall superior system performance.



FIGURE 6. Middle transverse (upper) and middle longitudinal (down) sections.

CONCLUSIONS

In this paper we have studied how the methods of topology optimization can be applied to obtain the conceptual designs of a mechatronic machine component. We investigated the interdependence between the volume fraction and the first eigenfrequency, which was the objective to be maximized in the optimization. It was found that, in the considered case, the optimizer does not find it attractive to allocate more than 88% of the material inside the optimization domain, which clearly shows a trade off between mass and dynamic properties of the system. However, mass itself also directly influences the dynamic properties of the overall controlled system. Therefore, the challenge becomes to fully integrate structural design and controlled system design. The wide range of designs that topology optimization can generate can be an important benefit to obtain the best possible system performance.

REFERENCES

- [1] Bendsøe M, Sigmund O. Topology Optimization - Theory, Methods, and Applications. Springer Verlag; 2003.
- [2] Chen CY, Cheng CC. Robust integrated design for a mechatronic feed drive system of machine tools. 2008;37:450–460.
- [3] Du J, Olhoff N. Topological design of freely vibrating continuum structures for maximum values of simple and multiple eigenfrequencies and frequency gaps. Structural and Multidisciplinary Optimization. 2007;34:91–110.

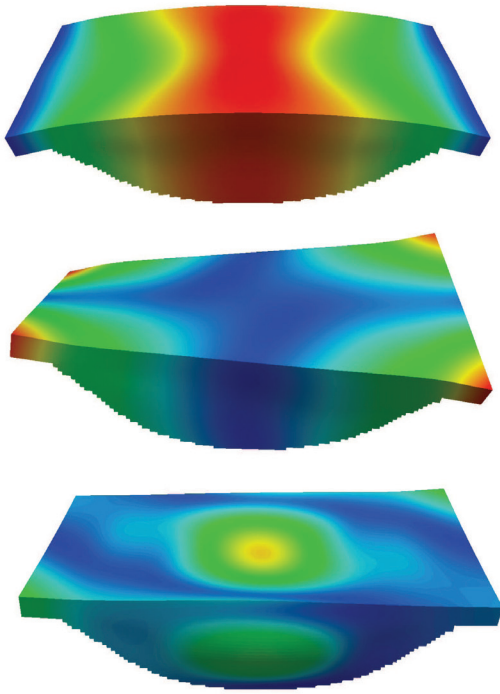


FIGURE 7. Three eigenshapes related to the lowest eigenvalues (lowest at top). The colors correspond to displacement amplitudes.

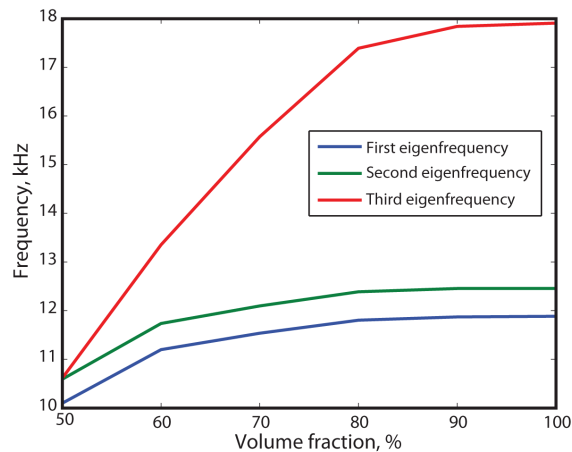


FIGURE 8. The three lowest eigenvalues of optimal designs for different volume fractions.

- [4] Andreassen E, Clausen A, Schevenels M, Lazarov B, Sigmund O. Efficient topology optimization in MATLAB using 88 lines of code. *Structural and Multidisciplinary Optimization*. 2011;43:1–16.

- [5] Svanberg K. The method of moving asymp-

totes - a new method for structural optimization. *International Journal for Numerical Methods in Engineering*. 1987;24(2):359–373.

FIBER-COUPLED 3-DOF INTERFEROMETER FOR EUV LITHOGRAPHY STAGE METROLOGY

Jonathan D. Ellis^{1,2}, Steven Gillmer¹, Chen Wang³, Richard Smith²
Shane C. Woody⁴, Joshua Tarbutton⁴

¹Department of Mechanical Engineering

²Institute of Optics

³Department of Electrical and Computer Engineering

University of Rochester

Rochester, NY, USA

⁴InSituTec Incorporated

45 Odell School Rd, Suite A

Concord, NC, USA

INTRODUCTION

The objective of this research is to demonstrate a compact heterodyne displacement measuring interferometer which can be used to measure the linear motion and rotational errors of an EUV lithography stage simultaneously. Heterodyne interferometry is ideal for this type of high speed stage feedback sensing because of its high dynamic range, high signal-to-noise ratio, and direct traceability to the meter.

There are a variety of benefits to fiber-delivered interferometers for high speed stage metrology. First, the alignment of individual interferometers are decoupled and the laser alignment is decoupled from the interferometers. The overall set-up can be divided into subsystems to more easily track down and rectify misalignments. Simplified alignment and division into subsystems increases stability of the structure because the metrology footprint is significantly reduced. Measuring the linear position and rotational errors along that axis can also reduce the number of interferometers required, further shrinking the metrology footprint. Also, the additional degrees of freedom provide avenues for self-calibrating of angular motions due to redundancy. Many beam routing optics can be eliminated and the heterodyne laser (a heat source) can also be isolated from the lithography stage. All of these factors result in increased productivity by reducing downtime. Figures 1 and 2 help to visualize the transition to a fiber-delivered and simplified interferometer setup.

In this proceedings, we present ongoing work towards a compact, three axis fiber-delivered heterodyne interferometer and phasemeter system. Our novel interferometer will utilize

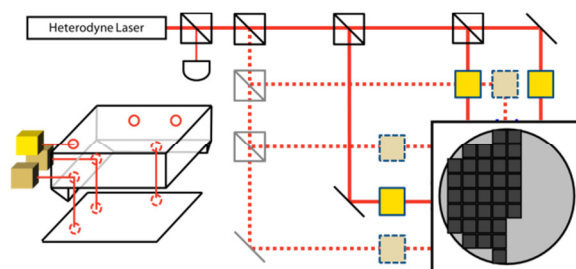


FIGURE 1. A common multiple interferometer setup used for EUV lithography stage metrology. Misalignments early in the beam path can easily propagate through the system. Dashed beam signify out of plane positioning.

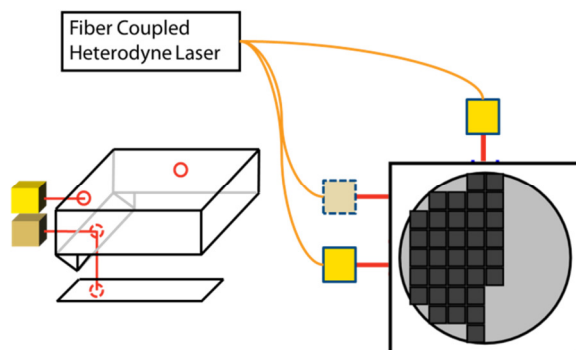


FIGURE 2. Fiber delivered interferometers simplify alignment, decrease the number of required beam routing optics, and increase stability by reducing the metrology footprint. Increasing the stability can lead to less down time.

differential wavefront sensing to measure target mirror displacement, tip, and tilt [1,2]. Differential wavefront sensing uses a single optical interference beam between the interferometer and target combined with a quadrant detector to measure four spatially separated interference

signals within a single interference pattern. Based on the geometry of the detector and the interference phase in each quadrant, the displacement and changes in target tip and tilt can be decoupled.

Differential wavefront sensing will need four separate phase measurements relative to a common optical reference, thus five simultaneous ADC channels will be incorporated into a single phasemeter board. Because this interferometer will be fiber-delivered, the phasemeter developed must be able to accommodate non-stationary heterodyne optical signals. We will present preliminary testing with a custom FPGA-based phasemeter which will enable high speed signal processing and communication with a standard host measurement PC using USB and Gigabit Ethernet.

ERROR CONSIDERATIONS

The three main error sources that limit the performance of a displacement interferometry system are the laser frequency stability [3], refractive index fluctuations in non-common optical paths [4], and periodic nonlinearity in the measured phase due to source mixing, manufacturing tolerances, and imperfect alignment [5-7].

For high speed positioning stages, the measurement uncertainty scales with the optical path difference between the measurement and reference arms in the main interference signal. Since EUV lithography operates in vacuum, the refractive index is defined as one, thus the measurement uncertainty from refractive index fluctuations is zero. Additionally, a high frequency stabilized laser can be used to limit displacement measurement uncertainties from laser frequency fluctuations to well below 100 pm. Thus, the limiting uncertainty contributor for the interference measurement is from periodic nonlinearity due to source mixing, imperfect coatings, and alignment.

In addition to the fundamental error sources in interferometers, there are also several other measurement error sources. One potentially large error source is the beam delivery optics which will have large force variations and stress variations as the EUV tool is pumped down to vacuum. These forces and stresses can cause misalignments that prevent the displacement interferometer from working properly because

the relatively long path length for beam delivery means small angular changes result in large deviations at the interferometer. Thus, fiber-delivered interferometers are desirable because they eliminate the long beam steering optical paths, simplifying the metrology frame and system. Thus, even though stress distortions are inevitable when a vacuum is pulled on the system, they are minimized because the path length in which they operate over can be limited. The hurdle we are attempting to overcome is a practical fiber delivered, periodic error free interferometer.

Previous research has shown that it is possible to build heterodyne interferometers with spatially separated beams to limit or eliminate periodic nonlinearity (e.g. [8-11]), including some configurations that are suitable for employing fiber-delivery to the interferometer [12]. This limits the coupling between free-space beam delivery components for multi-axis systems.

Fiber delivered interferometers have an additional drawback which is the input fiber induces artificial Doppler shifts to the optical reference and measurement signals. Traditional heterodyne interferometry has a nominally fixed optical reference signal and a measurement signal that fluctuates based on the optical Doppler shift induced by the moving measurement target. If the measurement target is not moving, then both the reference and measurement signals are nominally equal and constant. Fiber delivered interferometers have a continuously changing heterodyne frequency due to continuous fluctuations in temperature, stress, and vibrations on the input fibers. These perturbations are equal for both the reference and measurement interference signals but it places additional design considerations on the phase detection algorithm.

Another practical limitation is the readout electronics for the phase detection. Dedicated phasemeters for displacement interferometers are not user friendly and largely built on using a VME bus, something no standard computer has. This often leads to complex and dedicated controller systems which are costly to maintain in terms of components and expertise. Instead, communication through modern computer interfaces such as USB, Firewire, HDMI, and/or Gigabit Ethernet can increase the robustness of the phasemeter and controller while reducing costs.

All of the previously mentioned error sources have been considered in the design of our fiber-coupled tip/tilt sensitive interferometer. The following section will outline our testbench and discuss some preliminary data and observations from measurements made with our bench top displacement measuring interferometer.

SYSTEM SET-UP

A schematic of our compact, fiber delivered interferometer is shown in Figure 3. A commercial frequency-stabilized Helium-Neon gas laser is used as the source. The output beam is split through a 50/50 non-polarizing beamsplitter and directed towards two acousto-optic modulators (AOMs) which create the split frequency needed to obtain frequency modulated measurements. AOM₁ creates a first order diffracted beam which frequency shifts the input frequency up by 80.07 MHz. AOM₂ on the other hand creates a first order diffracted beam which frequency shifts the input beam up by 80.00 MHz. Therefore, the nominal split frequency created becomes 70 kHz when the beams eventually interfere. This split frequency was chosen because we were limited by the 100 kHz bandwidth of our lock-in amplifiers. In practice, we expect to use heterodyne split frequencies in the 10+ MHz regime to accommodate high Doppler shifts from high stage velocities and will be incorporated into our phasemeter system.

The first order, upshifted beams are then both fiber-coupled into polarization maintaining fibers which maintain a perpendicular polarization relative to the bench top surface. As previously stated, both fibers are prone to stress induced phase shifts as a result of mechanical and

thermal stresses. The phase shifts, denoted by θ_1 and θ_2 , can be kept nominally equal if the fibers are tied together, however, the fiber-induced phase shifts will never be the same. The benefits of a fiber-coupled interferometer can be seen at this point. In terms of alignment, the first non-polarizing beamsplitter, both AOMs, and both input fiber couplers are completely isolated from the rest of the interferometer. Therefore, a misalignment through an AOM, for example, will not necessarily propagate through the rest of the interferometer and can be corrected independently from interferometer alignment. Our system has been divided into two sub-systems to more effectively isolate and remedy misalignments.

Both beams are launched into the interferometer through two output couplers which are spatially separated to minimize the effects of frequency mixing [12] and the resulting periodic nonlinearity [5]. Our novel interferometer consists of two non-polarizing beamsplitters, which avoids additional frequency mixing from polarization-dependent components. The f_2 input beam is split in the top beamsplitter where 50% of the light is directed towards the quadrature detector to eventually be used for a measurement interference signal. The remaining 50% of the f_2 beam passes through the non-polarizing beamsplitter and reflects off a stationary reference mirror. Upon re-entry into the interferometer the reference beam is again split and 50% of the remaining beam is directed towards the reference photodetector to be used for a reference interference signal.

The f_1 beam traverses a similar path to the f_2 beam. After entering the interferometer, 50% of

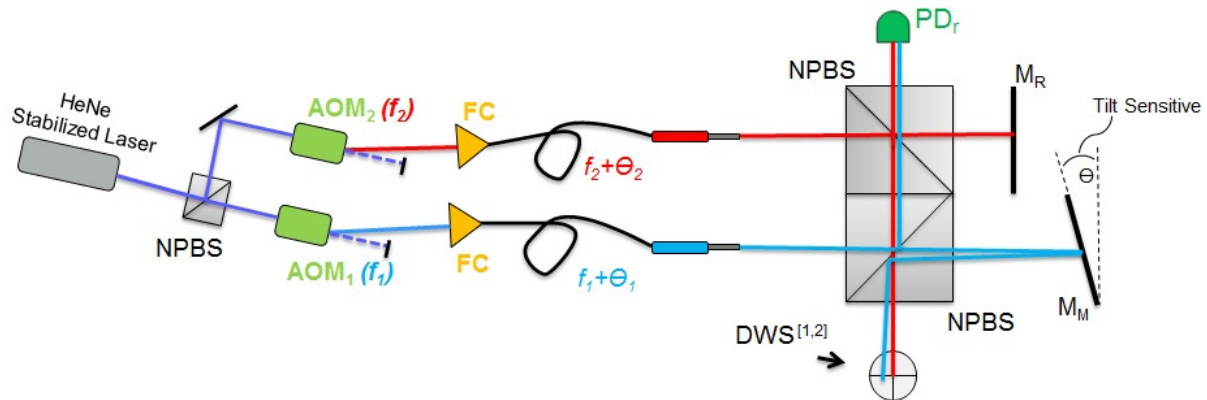


Figure 3. Schematic of our fiber coupled, three degree of freedom displacement interferometer. (NPBS: non-polarizing beamsplitter, AOM: acousto-optic modulator, FC: fiber coupler, PD: photodetector, M: mirror, DWS: differential wavefront sensing)

the f_1 beam is directed towards the top reference photodiode to be used for a reference interference signal. The remaining 50% passes through the interferometer to a measurement mirror where it is reflected. After 50% of the reflected measurement beam is reflected off the bottom non-polarizing beamsplitter it travels towards the quadrature detector with a tilted wavefront and Doppler shift with respect to the f_2 beam. The tilt angle is exaggerated in Figure 3 and in practice, the rotational error is desired to be minimal, thus we do not anticipate issues with excessive walk-off. The quadrature detector outputs irradiances from four detectors which can be post processed. Tip and tilt values are obtained using a weighted average over symmetrically adjacent pairings of detector elements while overall displacement is the total average over all four detectors. Figure 4 shows a photograph of the benchtop interferometer using two beamsplitters, a fixed mirror, and a piezo stage on modular optical mounts. Figure 5 shows an overhead photograph of the complete optical setup, including laser, AOMs, fiber couplers, and fiber collimators.

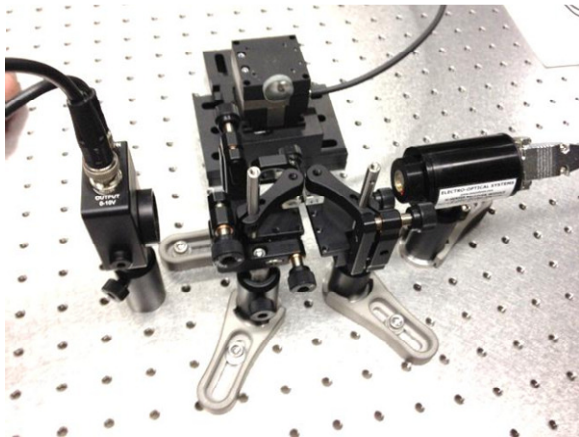


FIGURE 4. Close up photograph of the compact, three axis interferometer. The measurement mirror is attached to a piezo stage and the optical components are mounted to modular mounts for demonstration.

PRELIMINARY RESULTS

Initial measurements were made by slowly scanning the piezo stage (in open loop) to demonstrate displacement, pitch, and yaw sensitivity. Figure 6 shows a measurement of $\pm 35 \mu\text{m}$ with $\sim 10 \mu\text{rad}$ and $2 \mu\text{rad}$ of pitch and yaw motion, respectively. These measured results are within the specifications of our piezo stage. The rotational noise is approximately 100 nrad.

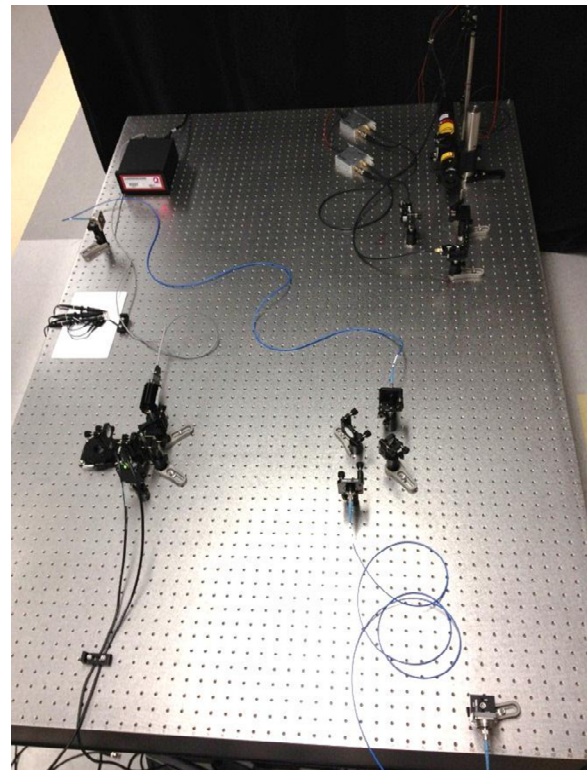


FIGURE 5. Overhead photograph of the source, fibers, and interferometer measuring the motion of a piezo stage.

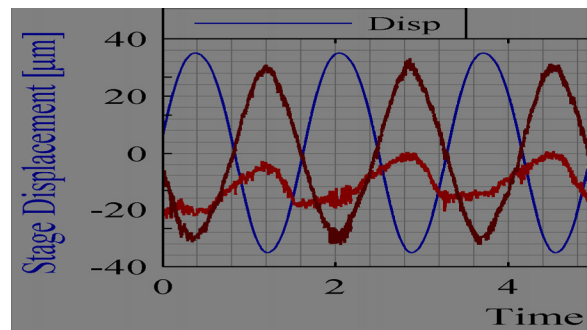


FIGURE 6. Initial measurement of the piezo stage in open loop scanning $\pm 35 \mu\text{m}$ with $\sim 10 \mu\text{rad}$ and $\sim 2 \mu\text{rad}$ of pitch and yaw motion, respectively

The measurement range for the rotational errors was assessed by placing the measurement mirror on a rotary stage (yaw) and manually rotating a micrometer thumbscrew. Figure 7 shows this result, where several hundred microradians of yaw rotation can be measured, which is considerable, given our interference spot sizes are on the order of 1.5 mm. While the measurement was in progress, the rotary table was rotated in an oscillating fashion. The measurement mirror was placed towards the

front of the rotary table so a rotation is not expected to produce a pure yaw motion; the oscillating displacement and corresponding pitch are expected. The results do, however, demonstrate that the interferometer has the capability to measure a broad range of microradian rotations.

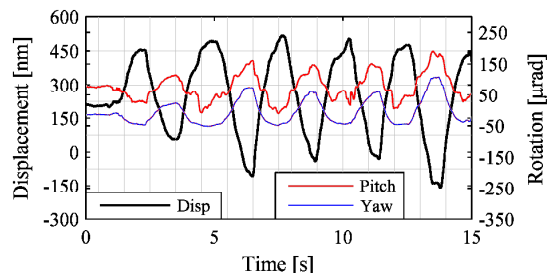


FIGURE 7. Preliminary pitch and yaw sensitivity of the interferometer. The measurement mirror was placed on a rotary table and manually rotated in an oscillating motion. Data axes have been offset for clarity.

The resolution of the system was assessed by holding the piezo stage at a constant voltage and the drift was recorded. Figure 8 shows the results of a stationary test to examine the noise level of the system. The linear displacement noise was approximately 10 nm, pk-pk while the rotational noise was approximately 400 nrad, pk-pk. These results were obtained using a time constant of 30 ms from the lock-in amplifier and are consistent with typical air current effects in uncommon optical paths. We expect this noise to be significantly reduced when a dedicated opto-mechanical system is devised, the environment is better conditioned (or in vacuum), and the heterodyne frequency is increased.

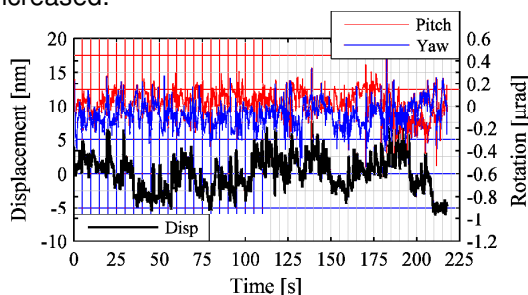


FIGURE 8. Preliminary noise measurements without filtering. Stage was held at a constant position. Data axes have been offset for clarity.

Our selection of a 70 kHz heterodyne frequency simplifies the phase measurement and data acquisition system while we are building our

custom phasemeter. However, the noise spectrum from our laser shows significant noise in the sub-megahertz regime, as shown in Figure 9. While the noise in Figure 8 is likely refractive index, the laser fluctuations can also contribute to errors and we will avoid this by shifting to a 5 MHz heterodyne frequency. This will rule out potential issues with laser fluctuations. Also, it will enable high velocity Doppler shifts to be measured.

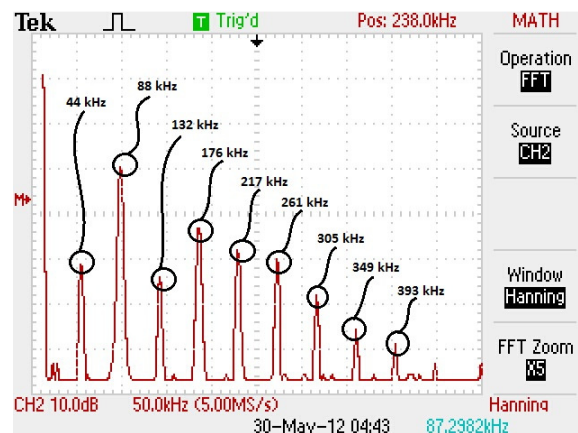


FIGURE 9. Fast Fourier Transform of the stabilized HeNe laser source used for our interferometer. A variety of undesirable kilohertz range frequency residuals are observed.

We have found that the overall resolution of the interferometer is limited by factors other than noise. Initial measurements yielded results displaying periodic nonlinearity, as shown in Figure 10. Although precautions were taken to design a configuration which, in theory, should be periodic error free (e.g. [8-11]), small periodic error persisted.

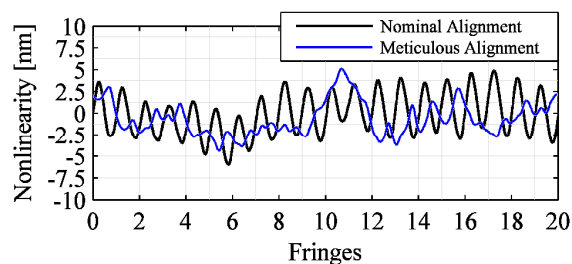


FIGURE 10. Periodic Nonlinearity was evident with the initial nominal alignment of the interferometer (black). After a more careful alignment periodic error was minimized further (blue).

Figure 10 shows that the periodic error was sensitive to alignment and we were able to reduce the periodic error significantly enough to

make it indistinguishable from refractive index fluctuations. However, this error was not eliminated. We are currently investigating the source of this error, as this interferometer should not be susceptible to periodic errors.

Preliminary hardware-in-the-loop simulations with our FPGA-based phasemeter demonstrate a noise level of 20 pm pk-pk, as shown in Figure 11.

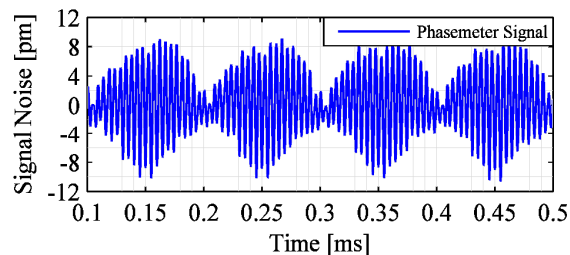


FIGURE 11. Phasemeter simulation at a 50 MHz sampling rate, 14-bit data width. Absolute resolution is on the order of ~20 pm pk-pk

The simulation was carried out with a 5 MHz heterodyne signal and a 10 kHz Doppler shift with 14-bit, 50 MHz sampling rates.

CONCLUSIONS AND FUTURE WORK

We have presented ongoing work towards the development of a fiber-coupled multi-degree of freedom displacement interferometer for high speed stage metrology. Preliminary results have proven that our interferometer configuration shows the potential to be a viable compact, three axis interferometer. The interferometer has demonstrated a ~250 μm range of pitch/yaw measurement while simultaneously recording z-axis displacement (Figure 7). Further optimization of the resolution of the system is still continuing.

Periodic error was shown to be alignment-sensitive. We are currently investigating potential sources, such as laser noise and wavefront sensing effects. Periodic error was not mentioned with other DWS interferometers [1,2] but it was not explicitly ruled out. We are in the process of implementing of our FPGA-based phasemeter capable of locking to megahertz-range reference signals. Eventually we will operate our system at a 5 MHz heterodyne frequency which will negate all unwanted residual frequency output from the laser source. Post process filtering with our custom phasemeter will further reduce signal noise as well.

REFERENCES

- [1] Müller H, wey Chiow S, Long Q, Vo C, Chu S, Active sub-Rayleigh alignment of parallel or antiparallel laser beams, *Optics Letters* 2005; 30: pp. 3323-3325
- [2] Schultdt T, Gohlke M, Weise D, Johann U, Peters A, Braxmaier C, Picometer and nanoradian optical heterodyne interferometry for translation and tilt metrology of the LISA gravitational reference sensor, *Classical and Quantum Gravity* 2009; 26: 085008
- [3] Bobroff N, Recent advances in displacement measuring interferometry, *Measurement Science and Technology* 1993; 4(9): pp. 907-926
- [4] Estler WT, High-accuracy displacement interferometry in air, *Applied Optics* 1985; 24(6): pp. 808-815
- [5] Quenelle RC, Nonlinearity in interferometer measurements, *Hewlett Packard Journal* 1983; 34: pp. 10
- [6] Hou W, Wilkening G, Investigation and compensation of the nonlinearity of heterodyne interferometers, *Precision Engineering* 1992; 14: pp. 91-98
- [7] De Freitas JM, Player MA, Polarization Effects in Heterodyne Interferometry *Journal of Modern Optics* 1995; 42: pp. 1875-1899
- [8] Wu C, Lawall J, Deslattes RD, Heterodyne Interferometer with Subatomic Periodic Nonlinearity, *Applied Optics* 1999; 38: pp. 4089-4094
- [9] Lawall J, Kessler E, Michelson interferometry with 10 pm accuracy, *Review of Scientific Instruments* 2000; 71: pp. 2669-2676
- [10] Joo KN, Ellis JD, Spronck JW, van Kan PJM, Munning Schmidt RH, Simple heterodyne laser interferometer with subnanometer periodic errors, *Optics Letters* 2009; 34: pp. 386-388
- [11] Joo KN, Ellis JD, Buice ES, Spronck JW, Munning Schmidt RH, High resolution heterodyne interferometer without detectable periodic nonlinearity, *Optics Express* 2010; 18: pp. 1159-1165
- [12] Ellis JD, Meskers AJH, Spronck JW, Munnig Schmidt RH, Fiber-coupled displacement interferometry without periodic nonlinearity *Optics Letters* 2011; 36: pp. 3584-3586

DIMENSIONAL METROLOGY OF PLASMONIC NANOLITHOGRAPHY MACHINE

Kang Ni, Robert J. Hocken
Center for Precision Metrology
University of North Carolina at Charlotte
Charlotte, NC, USA

ABSTRACT

A plasmonic nano lithography machine is being designed to implement the desired motion of flying plasmonic lens [1]. The precision positioning stage for plasmonic lithography requires dimensional metrology for its single degree of freedom motion. Related five degree of freedom errors from primary machine structure components are measured and integrated based on Homogenous Transformation Matrix. A thermal modeling plan is designed to characterize the response of machine due to temperature fluctuation in a room without temperature control, and that of the machine components like optical linear scale for future compensation and correction. Drift test and calibration of interferometer, capacitance gages and thermistors will be provided to validate the error correction in future.

MACHINE STRUCTURE OVERVIEW

The machine under development consists of a single degree of freedom motion with a spinning spindle-disc structure as a whole lithography system in Figure 1.

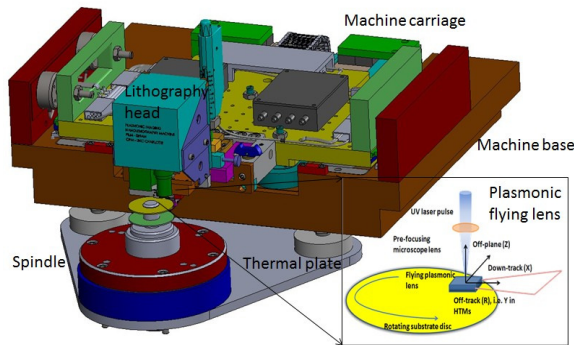


Figure 1 Machine structure and flying plasmonic lens

Driven by two linear motors underneath the carriage, the stage will be moving a flying plasmonic lens 15 nm above a photoresist disc spinning at 2000 RPM in the off-track direction covering 35 mm. Two linear optical scales on left and right sides of the carriage provide the basic

positioning information; one vertical wedge provides fine adjustment motion; and X-Y piezo actuators (3 um) provides final correction and location of a slider attached with the flying head.

GEOMETRIC ERROR MODELLING

Based on the rigid body assumption of machine structures, a single Degree of Freedom (DOF) motion would include six DOF parasitic errors: one linear positioning error, two perpendicular out of straightness errors and three angular errors (pitch, yaw and roll). The metrology loop illustrated in Figure 2 is consisted of base, carriage, wedge and shear PZTs which is closed at the center of spindle. Using HTM representation, it is straightforward to simplify high order error terms and extract those necessary ones to be measured [2-5].

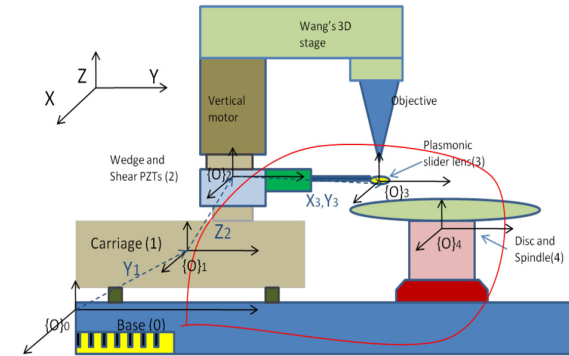


Figure 2 Metrology loop and coordinate system

The error can be written as the difference between commanded machine position and the practically measured machine location in a same coordinate system (i.e. the base system) as below.

$$E_{(0)} = P_{(0)c} - Q_{(0)e} = \begin{bmatrix} \delta_x(Y_1) + \varepsilon_x(Y_1) \cdot Z_2 - thermal_d \\ \delta_y(Y_1) + \delta_y(Z_2) - \varepsilon_y(Y_1) \cdot Z_2 + \alpha_{xz} \cdot Z_2 + thermal_{x_1} - thermal_r \\ \delta_z(Z_2) + \delta_z(Y_1) - thermal_h \\ 0 \end{bmatrix}$$

In fact, the Z direction deviation perpendicular to the primary Y motion can be neglected because the flying head is designed to follow the profile of spinning disc with a gap of about 15 nm.

THERMAL ERROR MODELING

Compared with deterministic modeling process, thermal error modeling is based on experimental information [6] collecting from four thermistors surrounding the location of spindle mount, laser beam and the two linear scales in Figure 3. The expansion of linear scale due to temperature change will be taken into account when software correction on positioning is needed without the measuring laser during the lithography procedure.

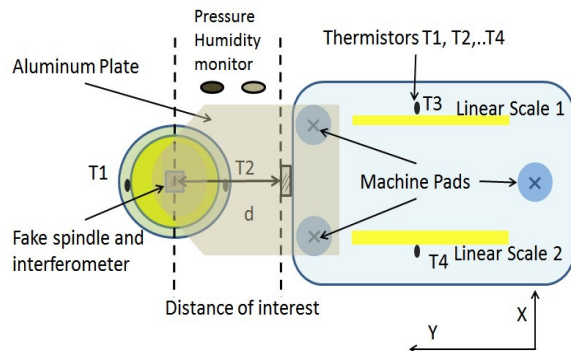


Figure 3 Thermal modeling and sensor location

ERROR MEASUREMENT PLAN

To measure all the significant geometric errors in the final HTM representation, a series of measurements will be implemented before the error integration in Table 1.

Table 1 Error measurement plan

Type	Symbol	Measurement plan
Linear positioning accuracy	$\delta_Y(Y_1)$	Plane mirror Interferometer (direct)
X straightness of Y of carriage	$\delta_X(Y_1)$	Single cap gage (direct)
Z straightness of Y of carriage	$\delta_Z(Y_1)$	Single cap gage (direct)
Roll angle of Y axis of carriage	$\epsilon_Y(Y_1)$	Double cap gages (differential manner)
Pitch angle of Y axis of carriage	$\epsilon_X(Y_1)$	Triple cap gages (combined differential manner)
Squareness of Z and Y of wedge	$\alpha_{Y_2Z_2}$	Observed and estimated by autocollimator (indirect)
Straightness of Z axis of wedge	$\delta_Z(Z_2)$	Integrated with the Z straightness of Y in carriage
Straightness of Y axis of wedge	$\delta_Y(Z_2)$	Integrated with linear positioning accuracy

Instruments like capacitance gages, interferometers and thermistors are used for the measurement in Figure 4.

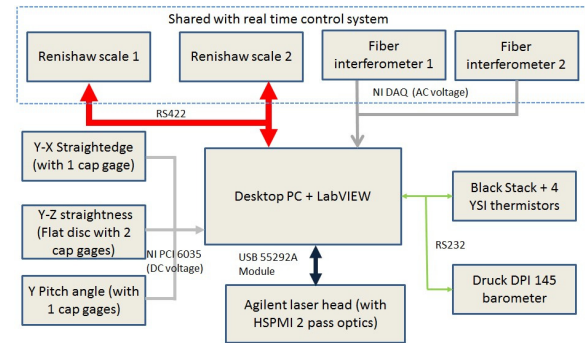


Figure 4 Block diagram of measurement system

MECHANICAL PARTS FOR METROLOGY

An independent metrology system works in off line style is needed for further software correction. Therefore, a variety of mechanical parts have been designed and machined to provide allocation, alignment and preload of related sensors, optics and reference artifacts from Figure 5 to Figure 7.

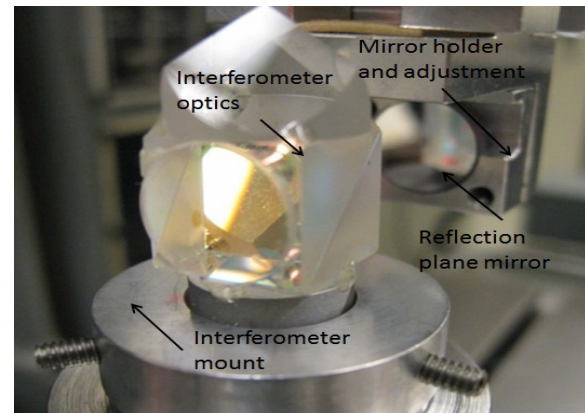


Figure 5 Plane mirror displacement measurement interferometer

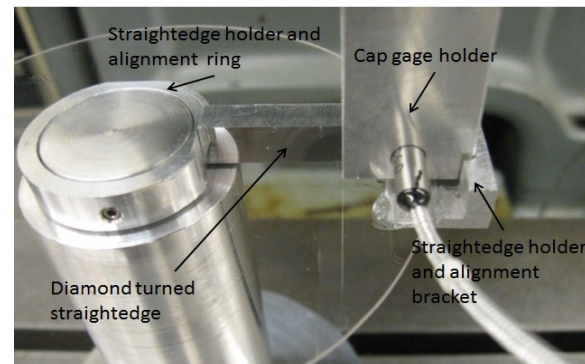


Figure 6 Straightedge reversal measurement setup

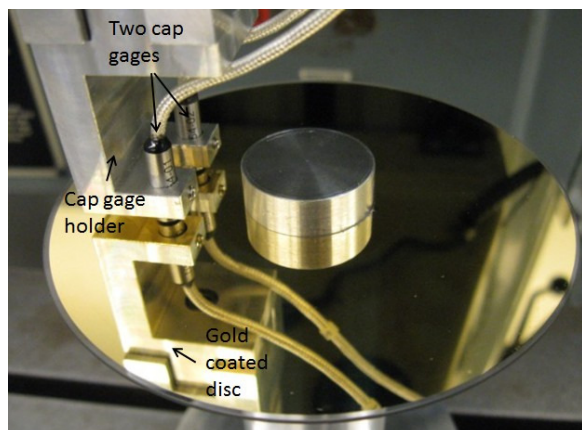


Figure 7 Roll angle measurement setup

Calibration and Compensation of the Metrology System

The capacitance gages were calibrated one year ago at NIST. It's not necessary to redo the expensive calibration again based on our application.

The temperature sensors have not been calibrated yet. Since they are NTC type semiconductor device i.e. the temperature-resistance coefficients are crucial to certain of temperature measurement range (around 20 degree based on lab condition), we need to build a system to calibrate and obtain those coefficients for extrapolation. A calibration tube is designed to fit the dry well with the thermistors attached interiorly and isolated from the outside. As indicated in Figure 8, the temperature will be feed into the Black Stack 1560 system which is connected to PC through serial port.

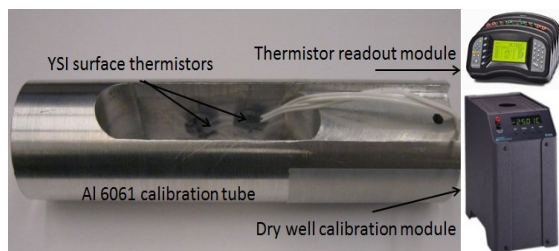


Figure 8 Thermistor calibration system

Although laser used in this study is not need to be frequency stabilized, the machine positioning resolution is 5 nm in without absolute length requirement which requires the correction of measurement due to the environmental factors like temperature, pressure and humidity [7].

FUTURE WORK

The developed setups will be tested under LabVIEW environment. An error table containing correction values will be generated and integrated with control algorithm. The repeatability of both geometric and thermal errors will be studied to validate the effectiveness of software correction.

ACKNOWLEDGEMENT

This work is supported by SINAM Graduate Young Investigator Award at University of California at Berkeley.

The authors appreciate the help and discussion from Greg Caskey, Jimmie Miller and John Brien. Mohamed Saad provided all the Solidworks models and Deepak Kohli and Eric Browy contributed to the diamond turning of the straightedge.

REFERENCE

1. Srituravanich, W., et al., *Flying plasmonic lens in the near field for high-speed nanolithography*. Nat Nano, 2008. 3(12): p. 733-737.
2. Hocken, R.J., *MEGR-7182 and 8182 Machine Tool Metrology and Selected Topics in Optics*, 2010.
3. Evans, C.J., R.J. Hocken, and W.T. Estler, *Self-Calibration: Reversal, Redundancy, Error Separation, and 'Absolute Testing'*. CIRP Annals - Manufacturing Technology, 1996. 45(2): p. 617-634.
4. Estler, T., *Validation Metrology of the Large optics Diamond Turing Machine*, D.o.C. U.S, Editor 1985: Gaithersburg.
5. Sartori, S. and G.X. Zhang, *Geometric Error Measurement and Compensation of Machines*. CIRP Annals - Manufacturing Technology, 1995. 44(2): p. 599-609.
6. Weck, M., et al., *Reduction and Compensation of Thermal Errors in Machine Tools*. CIRP Annals - Manufacturing Technology, 1995. 44(2): p. 589-598.
7. ASME, *METHODS FOR PERFORMANCE EVALUATION OF COMPUTER NUMERICALLY CONTROLLED LATHES AND TURNING CENTERS*, 1998: New York. p. 137-139.

VIBRATION SPECTRA AND ASYNCHRONOUS ERROR MOTION OF ULTRA-PRECISION AIR BEARING SPINDLES

Byron Knapp¹, Dan Oss¹, Dave Arneson¹, Mel Liebers¹, and Eric Marsh²

¹Professional Instruments Company

Hopkins, Minnesota, USA

²Machine Dynamics Research Laboratory

The Pennsylvania State University

University Park, Pennsylvania, USA

INTRODUCTION

Externally pressurized air bearings are used in precision metrology and manufacturing applications because of their inherently low synchronous and asynchronous error motions. This results from the error-averaging effect of the air films. While sub-micrometer error motions were sufficient early in the development of air bearing spindles [1], current semiconductor equipment requires nearly perfect rotation with only nanometer-level error motions [2]. The continuous demand for ever-improved performance requires continuous improvement of air bearing manufacturing and testing.

One important consideration in air bearing spindle design is the stability of the pressured air. Large amplitude air film instability (pneumatic hammer) has been addressed in the literature [3] and is largely solved in practice. However, broad-band vibrations on the picometer- and nanometer-levels remain a concern [4, 5]. This paper demonstrates the measurement and characterization of broad-band vibration to determine its relationship to asynchronous spindle error motion.

BACKGROUND

The air bearing spindle shown in Figure 1 has a 1024-count rotary encoder for commutation and data acquisition triggering (Renco) and a brushless, frameless motor and amplifier (MCS). The performance requirement of this spindle is 12 nm total radial and 12 nm total axial error at speeds from 500 RPM to 10,000 RPM. This is achieved on a production basis through precision engineering and manufacture with specialized metrology to resolve such small-amplitude errors.

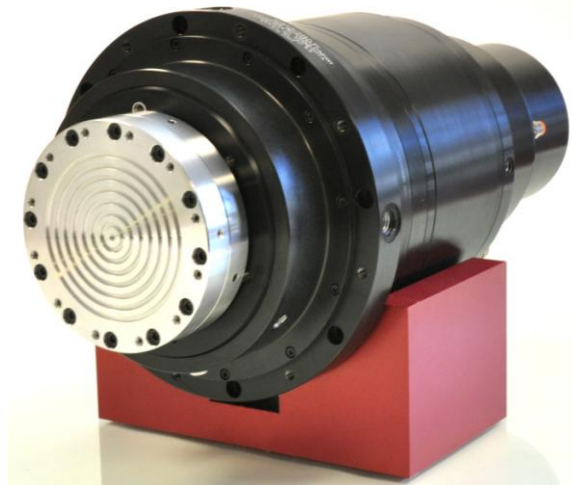


FIGURE 1. Professional Instruments Company ISO 5.5 motorized air bearing spindle used in this work.

Efforts to minimize asynchronous error motion led to our development of a test to measure broad-band vibration. The results have been used to evaluate design modifications. They are also used for systematic monitoring during the production assembly process.

APPROACH

To correlate broad-band vibration spectra and asynchronous error motion, the motorized spindle is mounted vertically in a granite testbed with passive air isolation as shown in Figure 2. A high resolution capacitive sensor (10 V/ μ m Lion Precision) targets the artifact in the axial direction using the tooling in Figure 3. Displacement vibration is measured for the non-rotating spindle at supply pressures from 0.4 MPa to 1 MPa.



FIGURE 2. A flange-mounted Ø25 mm lapped spherical artifact is mounted for vibration tests and error motion tests.

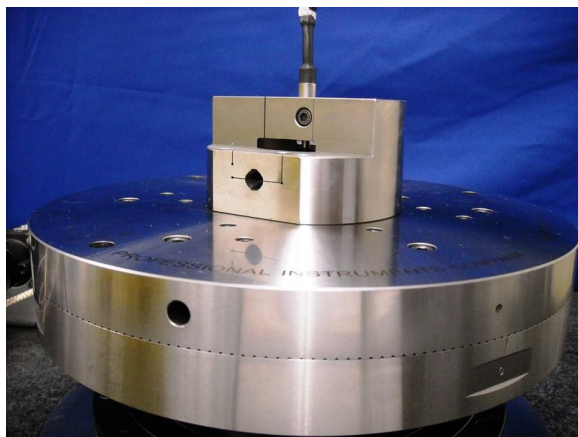


FIGURE 3. Tooling for measuring axial asynchronous error motion.

A dynamic signal analyzer (HP 35670A) is used to acquire time traces and linear spectra with a bandwidth of 6,000 Hz. Additional testing is carried out on the rotating spindle (500 RPM) to characterize asynchronous errors as a function of supply pressure. For these tests, data acquisition system (Lion Precision SEA) is synchronized to spindle rotation using the encoder signal. This synchronization is critical for accurate nanometer-level asynchronous measurements. Axial asynchronous error motions are measured at the same inlet air pressures as the previous tests. Characteristics of the displacement spectra are compared to asynchronous measurements to determine the relationship between the two.

RESULTS

Increasing the pressure from 0 to 1.0 MPa at the inlet to the air bearing clearly has an effect on the vibration level as shown in the time traces of Figure 4. Calculation of the standard deviation of the vibration level offers a convenient method to compare the amplitude at each pressure. Assuming a normal distribution, 99.7% of the values fall within $\pm 3\sigma$. The 6σ vibration amplitudes are summarized in Table 1. At low pressures, the vibration is barely above the noise-floor measured at 0 MPa. At pressures of 0.8 MPa and above, the vibration level increases dramatically, notwithstanding that the 6σ is less than 5 nm at 1 MPa. This phenomenon is present in all types of air bearings to varying degrees depending on design, compensation, and dynamic stiffness. It is a result of the increase in disturbing force acting on the system provided by the energy stored in the compressed air.

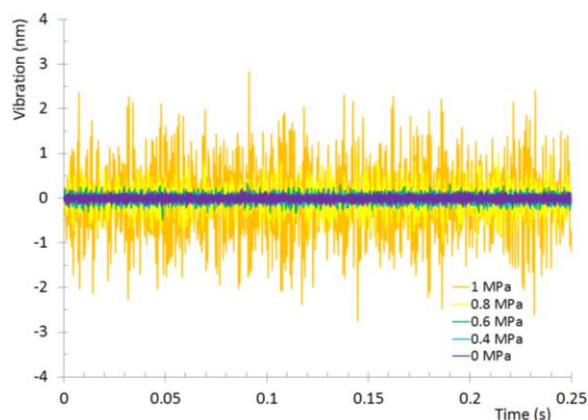


FIGURE 4. The time domain vibration amplitude provides a quick and intuitive measure.

TABLE 1. Summary of the time domain measurement results.

Pressure (MPa)	0	0.4	0.6	0.8	1.0
6σ vibration (nm)	0.4	0.5	0.6	1.8	4.7

In addition, it is instructive to measure the vibration levels in the frequency domain as the inlet air pressure is varied. The linear spectrum for each inlet pressure is shown in Figure 5. As with the time domain measurement, the frequency spectra rise quickly at pressures greater than 0.8 MPa. This type of measurement is used to evaluate design modifications and provide production process feedback. This spindle behavior can be represented as a single value for quick comparison by integrating the spectrum as shown in Table 2.

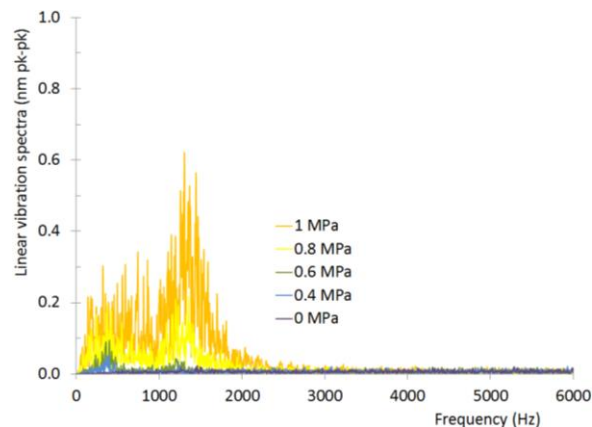


FIGURE 5. The time domain vibration amplitude increases as the inlet air pressure is increased.

These measurements of vibration are easier and more convenient to conduct on a production spindle during various stages of assembly. The results are used to provide immediate feedback to the manufacturing processes. By comparison, error motion tests are typically performed as the final step in lengthy production process making them less useful for timely feedback.

TABLE 2. Comparison of the frequency domain measurement results by integrated spectrum.

Pressure (MPa)	0	0.4	0.6	0.8	1.0
Integration (nm Hz)	19	23	28	70	162

Following the measurements of the spindle vibration, axial error motion tests were performed over the same range of inlet pressures [6]. A typical axial error motion measurement at 0.6 MPa inlet pressure and the

spindle running at 500 RPM is shown in Figure 6.

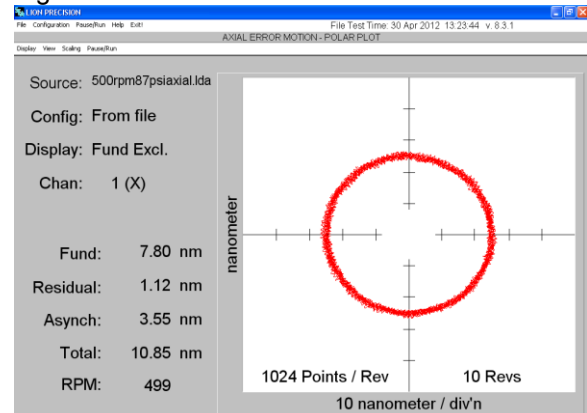


FIGURE 6. Axial error motion of a single test of 10 revolutions at 500 RPM with 0.6 MPa inlet air pressure.

At each inlet air pressure, the axial asynchronous error motion is measured 30 times over 10 revolutions at 1024 points per revolution. Thirty consecutive measurements of the axial asynchronous at 0.6 MPa are shown in Figure 7. The average axial asynchronous at each pressure is summarized in Table 3.

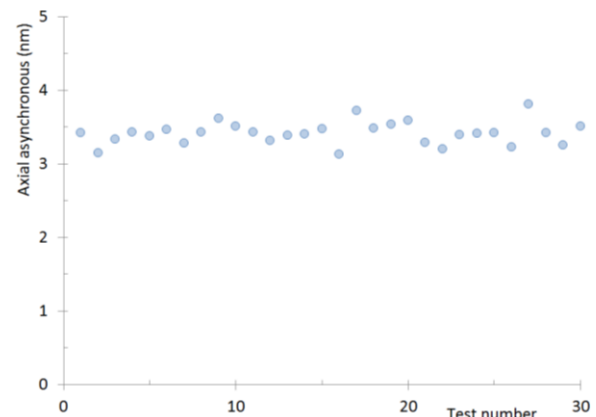


FIGURE 7. 30 axial asynchronous error motion measurements at 500 RPM with 0.6 MPa inlet air pressure. Average value is 3.4 nm.

TABLE 3. Summary of axial asynchronous error motion results at 500 RPM.

Pressure (MPa)	0.4	0.6	0.8	1.0
Axial asynchronous (nm)	2.1	3.4	6.1	11.2

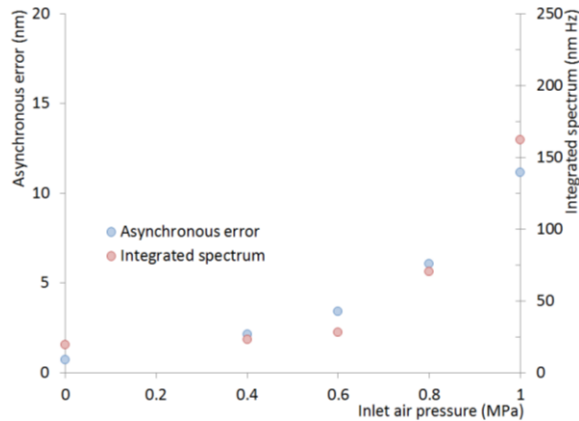


FIGURE 8. The rise in integrated spectrum with air pressure is consistent with the trend for asynchronous error.

When plotted on the same graph (Figure 8), there is an obvious relationship between the asynchronous error and the integrated spectrum.

CONCLUSIONS

Nanometer-level vibration levels of ultra-precision axes of rotation translate into asynchronous error motion. This paper demonstrates the measurement and characterization of these low amplitude vibrations and shows a relationship with asynchronous error motion. This measurement technique is a useful tool providing rapid feedback in our efforts to minimize asynchronous error.

REFERENCES

- [1] Ikawa, N, et al. Ultraprecision metal cutting- The past, the present and the Future. *Annals of the CIRP*. 1991; 40(2): 587-594.
- [2] van Eijk, J. Metrology and motion. *Proceedings of the ASPE Spring Topical*. 2008.
- [3] Stout, K, et al. The design of aerostatic bearings for application to nanometer resolution manufacturing machine systems. *Tribology International*. 2000; 33: 803-809.
- [4] Yoshimura, T, et al. Clarifications of the mechanism of nano-fluctuation of aerostatic thrust bearing with surface restriction. *Tribology International*. 2012; 48: 29-34.
- [5] Marsh, E, et al. Effects of gas composition on asynchronous error motion in externally pressurized spindles. *Precision Engineering*. 2008; 32: 143-147.
- [6] ANSI/ASME B89.3.4-2010. *Axes of Rotation; Methods for Specifying and Testing*. ASME New York: 2010.

Moving-Magnet Planar Motors for Next-Generation Lithography

Xiaodong Lu, Irfan-ur-rab Usman
Department of Mechanical Engineering
The University of British Columbia
Vancouver, BC, Canada

INTRODUCTION

In wafer lithography processes, a planar motion stage is used to carry a silicon wafer in a step-and-scan motion pattern. Typical requirements for a motion stage for this application include high speed (1 m/s), high acceleration (40 m/s^2), high precision (1 nm), long planar stroke ($>300 \text{ mm}$ in X and Y), and 6 degree-of-freedom (DoF) motion control [1]. Magnetically-levitated (maglev) stages have recently been used in commercial lithography machines, and are highly desired in extreme ultraviolet lithography (EUV) due to their vacuum compatibility. In this paper, we briefly review different existing solutions to maglev stages. Further, we introduce a new 6-DoF maglev stage with ultra-long planar stroke and compare its main features with prior art.

PRIOR ART OF 6 DOF MAGLEV STAGES

There are several pioneer works in the field of planar stages, such as a 3-DOF planar stepper motor [2] and a short-stroke 6-DOF maglev [3]. Here, we limit our discussion to 6-DoF stages with long planar stroke capability, i.e. strokes in X and Y over 300 mm.

Moving Coil Stages

Frissen *et al* described a moving coil stage, as shown in Fig. 1. The mover is comprised of four coil assemblies, and the stator is a 2-D Halbach array covering the working range of the stage. Embedded hall-effect sensors provide 6-DoF position feedback. The working area is determined by the size of the stationary magnet array.

Since the coils are installed on the moving stage, electrical power cables and usually some cooling tubes are attached to the moving stage to supply electrical current and remove the heat generated by the coils. These cables/pipes transfer disturbance forces directly to the mover and a secondary short-stroke 6-DoF stage is typically required to achieve precision motion. When multiple movers share a common magnet

base, these pipes/cables may block each other and constrain the usable range of each mover.

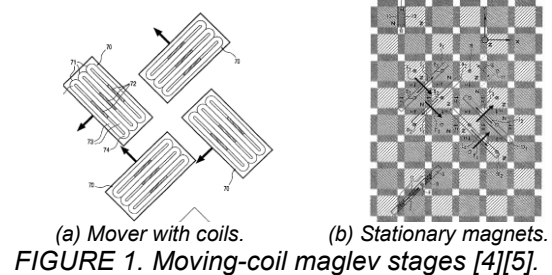


FIGURE 1. Moving-coil maglev stages [4][5].

Another issue in moving coil planar motors is that there is an intrinsic position dependent disturbance torque, as mathematically derived in [4]. As the moving stage travels laterally, forces on each moving coil will change due to the spatial-variation of the stationary magnetic field. The total force on each coil assembly can be easily maintained at a constant value with correct commutation of coil currents, but the force distribution relative to the center of gravity of the coil varies with mover position, producing spatially varying torques.

Moving Magnet Stages

By using a magnet array as the mover and leaving the coils stationary, a 6-DOF maglev stage can potentially be free of the above mentioned umbilical cord disturbances and spatially varying torques. For applications beyond lithography, the magnet stator with its strong exposed field is often a concern. Thus moving magnet designs may be used in a significantly wider set of applications. There emerged many concepts in patent documents during the last decade, with a few examples shown in Fig. 2. Philips is among the first to demonstrate a working prototype of a 6-DoF moving magnet stage with large stroke potential.

Most moving-magnet long stroke maglev designs in the literature share some common features: a two-dimensional chessboard-type magnet array is installed on the mover, and race-track shaped coils are arranged as a two-

dimensional array on the stator assembly. Careful examination of these designs reveals five issues.

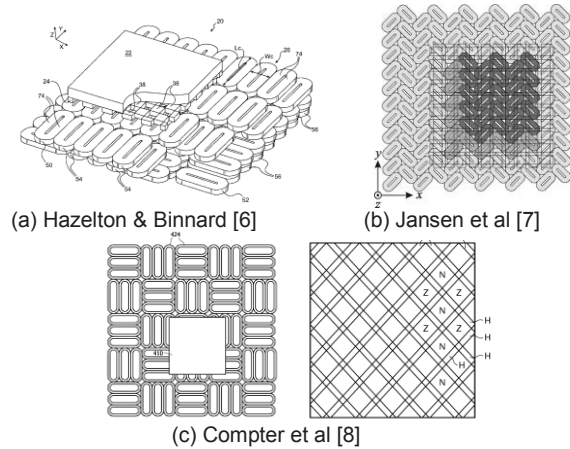


FIGURE 2. Prior art moving-magnet maglevs.

- Stage complexity (the number of required coils and thus the number of associated amplifiers and control outputs) increases quadratically with stroke. For example, when the stator assembly X and Y dimensions are doubled, its area and the number of coils will be quadrupled. The prototype in Fig. 2(c) was reported to have been controlled by software which took almost a decade to develop [9]. This indicates that such a design requires complicated software to handle current commutation among coils.
- The conductor filling-factor of race-track coils is rather limited; the inner portion of the racetrack footprint cannot be used effectively. Race track coils are difficult to produce with the center filled; even if this weren't the case, the center part will not contribute much force generation, as the current vectors along each side of the centerline of the racetrack coil oppose each other.
- There exist undesired force couplings caused by the interaction between coil end turns/return paths and three-dimensional magnetic fields. Strong coupling between multiple axes and disturbance torques are reported [10].
- The fringing field effect makes it difficult to commute coil current to generate three linear forces and three linear torques, as magnetic fields near the mover magnet array edge are very non-sinusoidal. A method used in [7] has to constantly vary the number of active coils between 15 and 24, which will produce non-smooth forces in scanning applications.

- Actuating force distribution on the mover is constantly changing with planar motion. For each portion of the mover surface area, the generated force direction is not determined by the mover but by the orientation of the coil immediately below that area. When the mover scans across the stator, each portion of the magnet array will see constantly varying coil orientations and thus will experience nearly step-wise changes in force directions. Even given an ideal commutation law to ensure constant forces on the overall mover, cyclic internal moments cannot be avoided in scanning due to the constant redistribution of actuation forces on the mover.

In the next section, a new moving magnet design is introduced to address all above-mentioned issues.

OMNIMOTION-XY

Figure 3 shows the concept of a moving magnet wafer stage. Four one-dimensional Halbach magnet arrays (X1, Y2, X3, Y4) are attached to a mover, with a stationary set of straight coils underneath. The stator is made of alternating stacks of coils arranged orthogonally in the X and Y directions. Each coil can be individually energized. The coils with driven currents (active) are shown in solid colours, and inactive coils (no current) are dashed lines. The zones of active coils change dynamically with the mover position in the stator plane. Each magnet array interacts with its corresponding active coils to produce actuation forces. Fig. 4 shows the cross-section of the Y2 magnet array and Y2 active coils. The magnet array is comprised of a typical series of vertically and horizontally magnetized elements, generating a Halbach array.

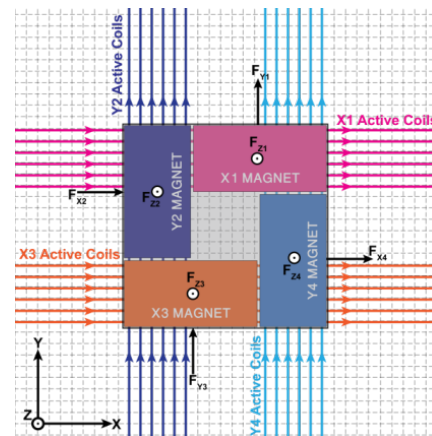


Figure 3: Electromagnetic configuration of 6DOF direct drive stage.

The advantages of using a Halbach array over an array with only vertically magnetized elements are 40% higher magnetic field strength and fewer higher order harmonic components in the field [11]. As the magnet array generates a periodic magnetic field on its bottom surface with both Z- and X- components, interaction of the field with current in the active Y-coils shown in blue will simultaneously generate a levitation force F_{Z2} and translation force F_{X2} on the Y2 magnet. Four magnets arrays generate two forces in X, two forces in Y, and four forces in Z for 6-DoF motion control. This coil array can be conveniently manufactured using cost-effective printed-circuit board (PCB) technology.

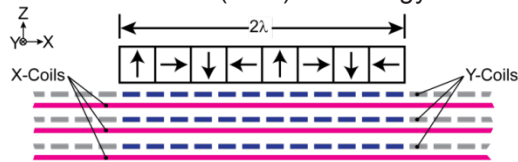


Figure 3: Cross-section of Y2 magnet array, inactive Y-coils in grey, active Y2-coils in blue, and X-coils in pink.

Next, we briefly review the advantageous features of this novel design over prior art and also point out the associated importance of these features in lithography applications.

Zero Force Coupling

Each magnet array generates forces in only its specified directions, and the force magnitudes are determined by only its corresponding active coils, without being affected by other magnet arrays and other active coils. For example, the Y2 magnet array in Fig. 3 has no net interacting forces with currents in X1/X3 coils under its bottom surface. Thus the magnet is fully decoupled from the orthogonal coils, greatly simplifying motion controller design. The active coils for the Y4 magnet array also won't interact with the Y2 magnet array, because any two magnet arrays of the same orientation are spaced apart such that the field edges of each array won't substantially intrude into the other array's zone. In addition, all coils have current return paths at the periphery of the stator, therefore the mover never experiences any coupling due to coil end turns. When the mover travels along the Y direction, the force produced by magnet array Y2 won't change at all because the Y-coils extend uniformly in the Y-direction for the extent of the working range.

Zero Effect of Fringing Fields

The magnetic field generated by a finite width magnet array is usually far from sinusoidal, especially near the edges for short array widths. With the field-folding method [12], the generated forces on each magnet array are equivalent to those between a finite width coil and an infinitely-long magnet array. As a result, the boundary effects are eliminated, greatly simplifying force modeling and controller design.

Linear Complexity with Planar Stroke

The number of coils is proportional to the peripheral length of the stator coil array, not the area of the stator. This design allows the planar motor to be easily extended in both X and Y directions for various applications while the number of required coils increases linearly with the X/Y stroke, instead of quadratically. This feature allows significant cost saving for large stroke applications.

Invariant Force Distribution on Movers

The force distribution on the mover is position independent. For example, as the mover travels in the X-direction, the current distribution of active Y2 coils will travel with the Y2 magnet at the same speed given proper commutation. Consequently, the Y2 current distribution is synchronous with mover motion in X, and thus the field generated by the active coils becomes invariant in the moving frame, and no position dependent torques or forces are generated. This feature significantly reduces position-dependent structural deformation on the mover and helps improve motion control precision. This opens the possibility of eliminating a secondary fine-motion stage usually required in wafer steppers.

High Overall Filling Factor

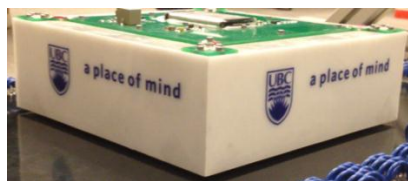
Unlike race-track coils, linear coil strips can be distributed on the stator surface side by side with the minimum gaps set by the PCB etching process. The insulation between coil layers can be reduced to 100 μm to minimize non-copper area. The cross-section of each coil is very close to rectangular shape, instead of circular as in conventional coil assemblies. Thus the overall volumetric copper filling factor (conductor volume over the whole stator volume) of a first prototype achieves over 60%. This high filling factor will translate into higher force density and higher acceleration capability.

Compatible with Mass Production

Coil arrays are manufactured using a commercial PCB manufacturing process, which can provide significant advantages in cost. More importantly, there is no need to separately align each coil in X/Y/Z/pitch/yaw/roll and control spacing between coils, as required in race-track coil designs. Here, all coils are already well aligned with micron level accuracy. This feature allows very precise placement of coils and minimizes the undesired force disturbance caused by the deviation between actual coil position/orientation and its ideal location. At the same time, the stator assembly cost can also be greatly reduced.

Enlarged Thermal Sink/ Improved Dissipation

In race-track coil designs, heat is generated in individual coils and kept there by insulation; the thermal conduction capability of neighboring non-active coils does not help the working coils. In the presented design, a PCB coil board is very similar to a solid copper plate, which helps spread heat to the entire stator board surface. This thermal sink effect can greatly improve the current carrying capability of active coils and thus increase acceleration. It should be noted that in the presented design Ohmic heat is generated beyond the mover area whereas no heat is generated by race-track coil designs in coils not underneath the mover. However, considering its quadratically-enlarged thermal sink area compared to its linearly-increased heat generating region, the advantage of PCB straight coils is still obvious in terms of thermal dissipation. The presented design can easily sustain several g's acceleration without active cooling, and by implementing an active cooling base can reach in excess of 10g as demanded by EUV lithography.



(a) Mover levitated 2.5mm above the stator.



(b) A side view of stator coil.

Figure 5: A working prototype planar motor.

Simplicity

The features discussed above allow simple installation and simple force generation,

obviating the need for complicated modeling, compensating for intricate coupling, and complex commutation algorithms. A prototype planar motor has been constructed: after receiving the required magnet components and PCB boards, it took 30 days to assemble the magnet array and the coil assembly; it took another 3 days to fly this prototype with 6-DoF active motion control, including plant modeling, control algorithm design, coding, implementation, and experimental verification. This experience demonstrates the simplicity of the presented long-stroke planar motor design.

REFERENCES

- [1] Butler H. Position Control in Lithographic Equipment. IEEE Control System Magazine, Oct. 2011: 28-47.
- [2] Sawyer, B., Magnetic Positioning Device, 1968, US Patent 3376578.
- [3] Kim, W., Trumper, D., 1998, High-precision magnetic levitation stage for photolithography, Precision Engineering, 22/2: 66–77
- [4] Compter, J. Electro-dynamic planar motor, Precision Engineering, 2004: 171–180.
- [5] Frissen, P. et al, Displacement device, 2005, US Patent 6847134.
- [6] Hazelton, A., Binnard, M., and Gery, J., "Electric motors and positioning devices having moving magnet arrays and six degrees of freedom," 2001 US Patent 6208045.
- [7] Jansen, J., van Lierop, C., Lomonova, E., and Vandenput, A., "Modeling of magnetically levitated planar actuators with moving magnets," 2007 IEEE Trans. Magn., vol. 43, no. 1.
- [8] Compter, J., Frissen, P., van Eijk, J., Displacement device, 2011, US Patent 7948122.
- [9] "Maglev stage promises nanometer precision", Drives and Controls Magazine, 2006 November.
- [10] van Lierop, C., Jansen, J., Damen, A., van den Bosch, P., "Control of Multi-Degree-of-Freedom planar actuators", Conference of Control Applications, 2006.
- [11] Trumper D., Nguyen T. Magnet arrays for synchronous machines. IEEE Industry Applications Society Annual Meeting, 1993: 9-18.
- [12] Lu, X.-D., Usman, I., A Novel Long-Stroke Planar Motor, 2011, Proceedings of ASPE Annual Meeting.

RECENT DEVELOPMENTS AND COMPARATIVE EVALUATION OF LORENTZ AND RELUCTANCE ACTUATORS FOR HIGH PRECISION SEMICONDUCTOR EQUIPMENT STAGES

Adrian Toma¹, Funda Sahin¹, and Marcel Renkens¹

¹Mechatronics

Philips Innovation Services
Eindhoven, The Netherlands

INTRODUCTION

High precision semiconductor equipment stages are confronted nowadays with increasingly tough and conflicting requirements with respect to accuracy, throughput and position modules (stages) footprint.

While the Moore's law is continuously increasing the required accuracy the chip manufacturers' economics make them ask for higher productivity by higher number of exposed wafers per hour and by larger wafer size.

Consequently the semiconductor equipment manufacturers are facing the requirement of moving larger (mass and footprint) positioning modules with higher acceleration and speed while achieving better accuracies.

These conflicting requirements are placing a heavy burden on the actuators used within the positioning modules with respect to dissipated power, thermal performance and power electronics roadmap developments to sustain these trends.

Historically Lorentz actuators are widely used to achieve the highest accuracy level within the positioning modules. However the sustained drive for higher force density has made the reluctance actuators a serious alternative despite their other shortcomings.

We will make a short comparative analysis of two types of electromagnetic actuators (Lorentz and reluctance) applied to high precision semiconductor equipment stages emphasizing their specific working principle and their advantages and disadvantages. Finally some examples and results of internal developments within Philips Innovation Services will be discussed.

COMPARATIVE ANALYSIS

The ideal electromagnetic actuation principle highly desirable for high precision semiconductor equipment applications will have a linear relation between force and current ($F=K \cdot I$) with a motor constant K independent of position, current level, speed, temperature, tolerances and environment.

Lorentz actuators

The Lorentz actuation principle is based on force exerted on current carrying windings situated within a magnetic field ([1]) which can be easily described by the following formula

$$\vec{F} = \vec{K}_{linear} I + \vec{K}_{quadratic} I^2$$

where the force part linear with the current (desirable within high precision systems) is the most dominant part while the force part quadratic with the current is very small being caused by parasitic effects (among others the reluctance effect of the backiron material behind the permanent magnets, magnetic field non-uniformity, etc.).

One typical example of a Lorentz actuator used for short stroke stages within high precision semiconductor equipment is shown in Figure 1 composed of coils, permanent magnets and ferromagnetic steel. The Lorentz type of actuation is the closest type of actuation to the ideal electromagnetic actuator. However as required accuracy within high precision systems increases small adverse effects (position dependency, damping, tolerances, temperature dependency and stray fields) of this type of actuator become important.

Its advantages for high precision applications in linearity, easy software implementation and accuracy have prevailed against its drawbacks until now.

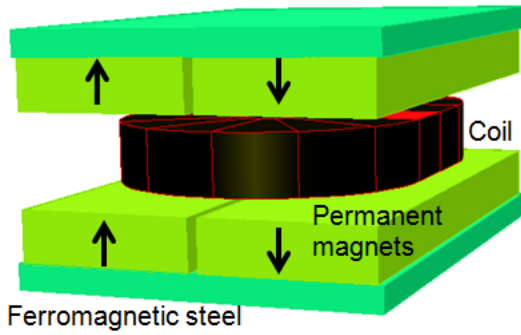


FIGURE 1. Lorentz type of actuator.

Within high precision systems using Lorentz actuators typical values for current density are up to 50 A/mm² and for magnetic field strength up to 0.7 T.

The major disadvantage of the Lorentz type of actuator is the relatively low force density and steepness which results in high power dissipation. This weakness combined with the foreseen roadmap of higher accelerations and moving mass will thermally challenge (see Figure 2) the Lorentz actuators used within future high precision systems.

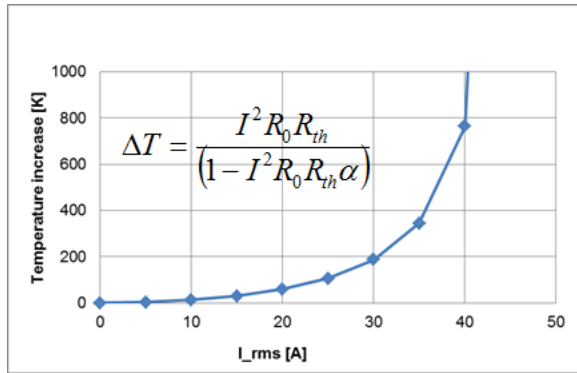


FIGURE 2. Thermal impact of higher power dissipation on an example Lorentz actuator ($R_0 = 2.4 \Omega$, $R_{th} = 0.050 K/W$, $\alpha = 4e-3K^{-1}$).

An overview of the state of the art values of the performance parameters for the Lorentz actuators applied to high precision systems is shown in Table 3.

Reluctance actuators

The reluctance type of actuation principle is based on attraction force exerted on a ferromagnetic mover by a ferromagnetic armature magnetized by a coil (see one

example of reluctance actuator in Figure 3) which can be easily described by the following formula

$$F = C_1 \left(\frac{n \cdot I}{2g + C_2} \right)^2$$

where n is the number of windings of the coil, I is the coil current, g is the airgap clearance and C_1 and C_2 are constants.

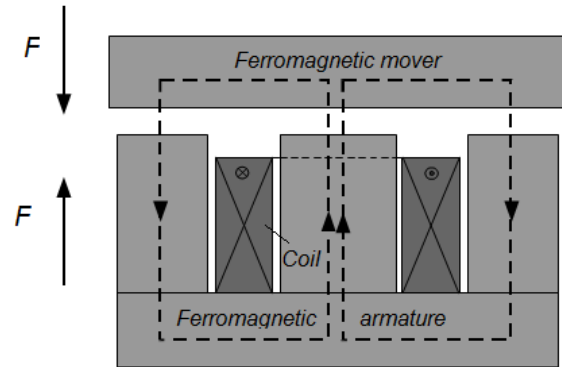


FIGURE 3. Reluctance type of actuator.

The disadvantage of this standard configuration is that it only generates an attracting force and no repelling force while for position control bidirectional force generation is desirable. For horizontal actuation the obvious solution is to place two actuators back to back. For the vertical actuation a more elegant solution is to integrate gravity compensation by introducing a permanent magnet (see Figure 4). In this configuration the generated force can be described by the formula

$$F = C_1 \left(\frac{h_m H_c + n \cdot I}{2g + C_2} \right)^2$$

where n is the number of windings of the coil, I is the coil current, g is the airgap clearance, $h_m H_c$ is the field strength of the magnet and C_1 and C_2 are constants. Consequently a force offset is introduced which enables bidirectional actuation (see Figure 5).

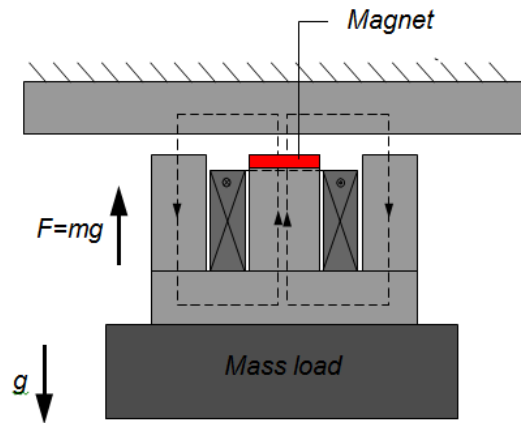


FIGURE 4. Bidirectional reluctance type of actuator combined with gravity compensation.

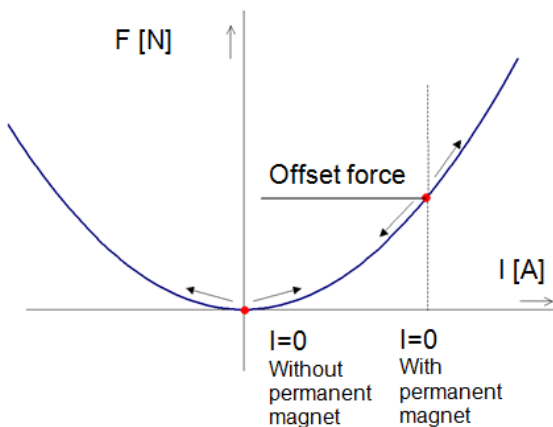


FIGURE 5. Bidirectional actuation enabled by permanent magnet gravity compensation within a reluctance actuator.

The non-linear force-current and force-gap relations and the high force variation are the major reasons why the reluctance type of actuators has not been implemented in the past in high precision systems. Previous publications ([2]) have highlighted these shortcomings. However, recently we have made successful use of this type of actuators at Philips Innovation Services within specific industrial applications ([3], [4]) which highly benefited from it (see Figure 6). These applications have valued more the reluctance type of actuation advantages like high force density, high steepness and low power dissipation against the disadvantages. This is also due to the fact that appropriate measures were taken to compensate the inherent adverse effects of the reluctance

actuators. This will be further explained in the following section.

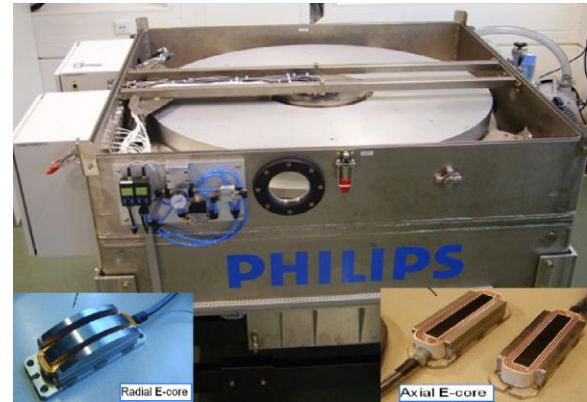


FIGURE 6. Rotary magnetic levitation stage for KLA prototype REBL e-beam writer using bidirectional reluctance actuators enabled by permanent magnet gravity compensation ([4]).

A specific disadvantage of the reluctance actuators is the hysteresis behavior caused by the hysteresis intrinsic to the ferromagnetic materials that are used for the armatures (see Figure 7). Moreover, the impact of this effect on the performance (see Figure 8) becomes even larger as there is usually spreading among the quality of the ferromagnetic material properties due to the manufacturing process and the thermal treatments applied to the material.

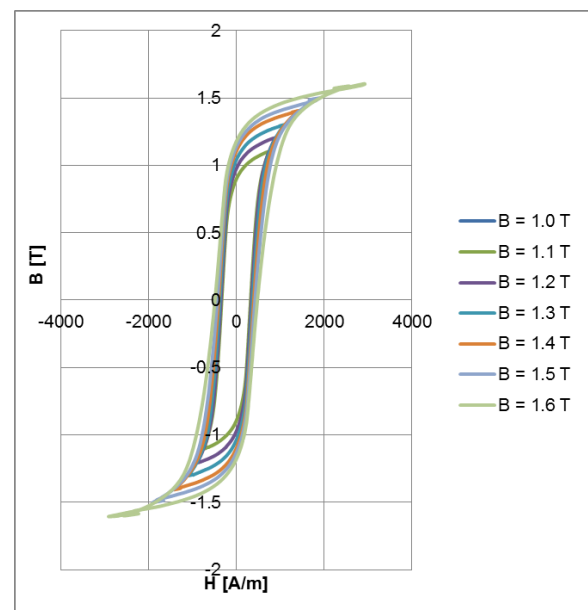


FIGURE 7. Measured hysteresis curves of ferromagnetic material.

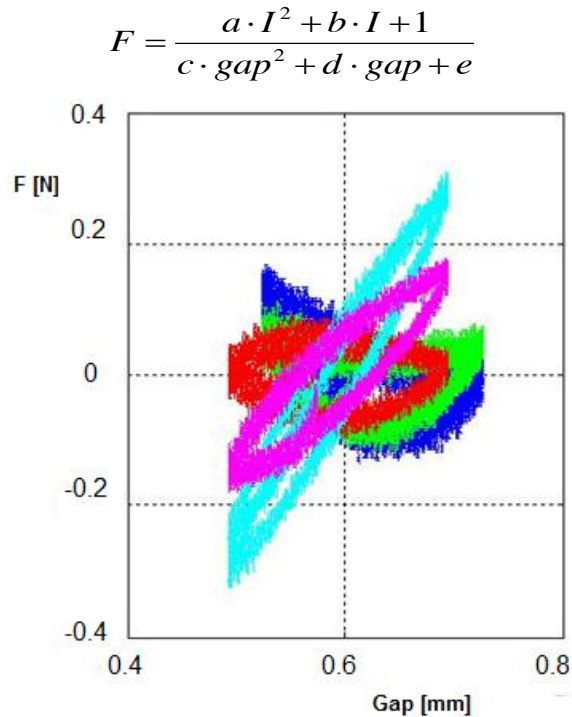


FIGURE 8. Typical hysteresis behavior of the reluctance actuators (example in current control mode).

An overview of the state of the art values of the performance parameters for the reluctance actuators applied to high precision systems is shown in Table 3.

RECENT DEVELOPMENTS

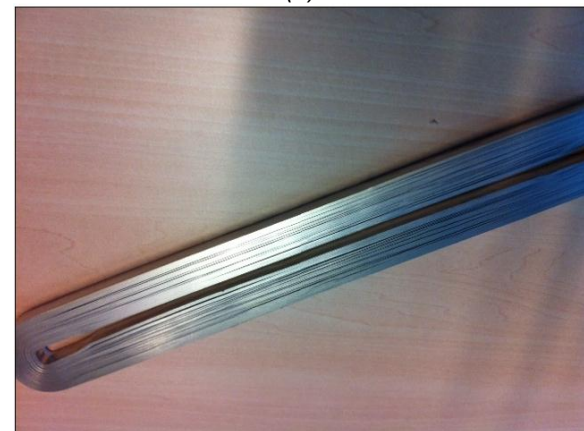
During the last decade significant performance improvements have been achieved. These performance improvements are mainly in the field of increasing the force density of the actuator as well as in reducing the parasitic effects. This has been realized by geometry optimizations, the application of different materials and increasing the cooling capabilities.

One industrially successful example of increasing steepness density of a Lorentz actuator based on internal developments within Philips Innovation Services (see Figure 9) is the implementation of foil coils (as well copper as aluminum) instead of the classical copper wires.

The superior packing factor of the foil coils is shown in Table 1. The thermal uniformity of the heated coil will improve significantly (see Table 2) and consequently will reduce the undesired hot spots.



(a)



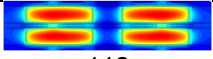
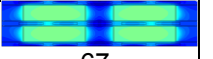
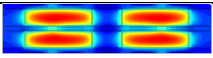
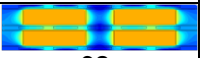
(b)

FIGURE 9. Copper (a) and aluminum (b) foil coils.

TABLE 1. Typical packing factor achieved within coils for Lorentz actuators applied to high precision systems.

	Packing factor coils
	[%]
Copper wire	<70
Aluminum foils	<90
Copper foils	<80

TABLE 2. Thermal uniformity of aluminum foil coils vs. copper wires.

Tmax [°C]	Copper-wire-winded coils	Aluminum-foil-winded coils
Same heat load	 112	 67
Same force (current density)	 112	 92

The following example illustrates the reduction of the adverse effects inherently present within reluctance actuators applied in high precision semiconductor equipment based on built up experiences and recent developments at Philips Innovation Services.

The disadvantages of the reluctance actuator are the nonlinearity of the force-current relation, nonlinear position (gap) dependency of the force, the cumbersome software compensation effort and hysteresis behavior. Traditionally there are two methods of controlling the reluctance actuator. One option is to use flux control (see Figure 10) which makes the force gap independent. In our implementation we integrated a Hall sensor element into the armature to measure the flux. This method is simple and requires little software compensation effort but it has the drawback of analogue calibrations and the final negative stiffness reduction is only 80% (due to implicit limited accuracy of flux measurement in our implementation). A second more effective option is to use current control (see Figure 11) which makes the force strong gap dependent. This can be compensated by using a sensor to measure the airgap. This method reduces the negative stiffness significantly (by 99%). On the other hand it requires more complicated software compensation effort as all the implemented calibrations are made in software.

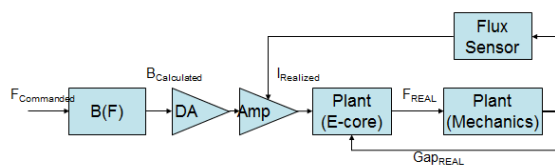


FIGURE 10. Flux control diagram of a reluctance actuator.

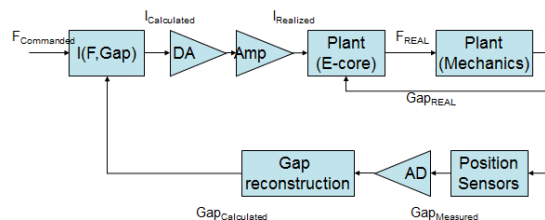


FIGURE 11. Current control diagram of a reluctance actuator.

Due to the fact that the reluctance actuators are utilizing ferromagnetic materials for force generation both in the moving and in the stationary part, if not carefully designed, large amounts of damping forces can occur in the actuator. In recent applications, novel laminated steel topologies were implemented where eddy currents were minimized within the actuator ([3]). For reluctance actuators with complex topologies, unconventional powdered iron materials can be used for reducing damping forces.

CONCLUSIONS AND EVALUATION

The actuators used in high precision applications have come a long way from simply electro-motors to become mechatronic system components which achieve accuracy by being robust against disturbances and having a highly predictable behavior.

Comparison of the state of the art values of the performance parameters for the Lorentz and reluctance actuators applied within high precision semiconductor equipment is shown in Table 3.

TABLE 3. Typical performance parameters for Lorentz and reluctance actuators applied to high precision systems based on actuators developed within Philips Innovation Services.

Parameter	Unit	Lorentz	Reluctance
Steepness density	$[N^2/W/m^3]$	$\sim 1e6$	$\sim 8e6$
Stroke sensitivity of motor constant	$[\%/mm]$	± 1	± 300
Parasitic stiffness	$[N/m]$	$10 \div 70$	$3000 \div 4600$
Parasitic damping	$[Ns/m]$	$0.1 \div 5$	$23 \div 46$
Tolerances impact on motor constant	$[\%]$	± 6	± 10

Clearly the reluctance actuators have an almost one order of magnitude higher steepness density indicating better performance parameters in force density and power dissipation. However these advantages come at a significant cost in adverse effects such as parasitic stiffness and damping and actuator sensitivity to tolerances and movements. The

latter strongly indicates the care and attention which have to be paid as well at actuator level as at system level when applying these actuators in high precision positioning systems. Careful judgment in selecting the performance relevant effects to be compensated and in deciding upon the implementation method of these compensations in software has to be considered.

To meet future requirements Lorentz actuators developments should address thermal management improvements by e.g. applying different coil topologies, novel forcer built-up and innovative cooling strategies.

On the other hand reluctance actuators should further build upon advanced control strategies (profiting from developments in computing power and software flexibility), accurate sensing systems and new armature designs.

REFERENCES

- [1] Compter J C, Frissen P C M. Displacement Device. Patent WO01/18944/Patent WO01/191204/ Patent EP1135846. 2001.
- [2] Vrijssen N H, Jansen J W, Lomonova E A. Comparison of linear voice coil and reluctance actuators for high precision applications. 14th International Power Electronics and Motion Control Conference. 2010.
- [3] Sahin F, Bustraan K, Seijger O, Post J. A Magnetic Bearing, a Rotary Stage and a Reflective Electron Beam Lithography Apparatus. WIPO Patent Application WO/2010/122450. 2010.
- [4] Petric P, Bevis C, Brodie A, Carroll A, Cheung A, Grella L, McCord M, Percy H, Standiford K, Zywno M. REBL nanowriter: Reflective Electron Beam Lithography. SPIE. 2009.

AN ALTERNATIVE PERMANENT MAGNET BRUSHLESS MOTOR ARCHITECTURE

Ty Safreno¹, Troy Kelley², Richard Goldsmith³

¹ Trust Automation Inc.
San Luis Obispo, CA USA

² Trust Automation Inc.
San Luis Obispo, CA USA

³ Trust Automation Inc.
San Luis Obispo, CA USA

INTRODUCTION

In 2011 there were over 650 million electric motors sold in products or factories in the United States. Each of us purchased several electric motors, likely without realizing or appreciating we did. These electric motors vibrate mobile phones, run toys, enable cordless tools and are the future of transportation to name but a few applications.

Electric Motors can be classified in a simple tree diagram. This covers all of the existing classifications and variations of those.

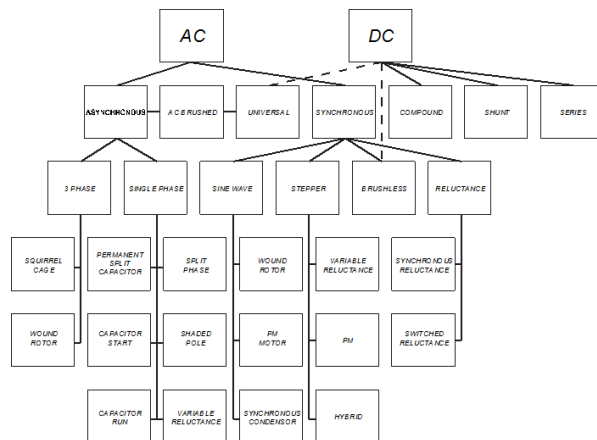


Figure 1: Electric Motor Classification Tree [1]

Although Permanent Magnet Brushless Motors (PMBM) are only a small segment of annual motor sales, it is still an important and significant business segment which exhibits strong growth year over year.

For the last 20 years PMBM's have remained relatively the same from a magnetic machine standpoint. There have been variations to the base design, but the majority of these efforts either stopped in the lab, or could never get the traction necessary to build a sustaining large scale competitive edge.

Some of these novel configurations are shown below. Even though these are not the focus of this paper they give background to the diverse directions the industry is already taking.

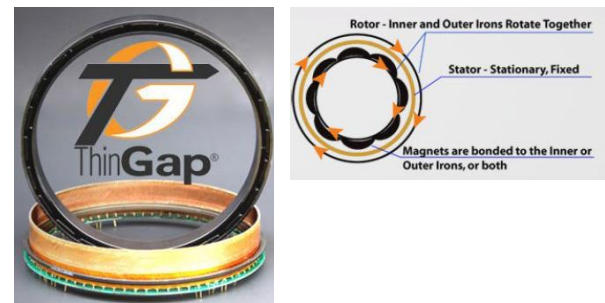


Figure 2: ThinGap Motor [2]

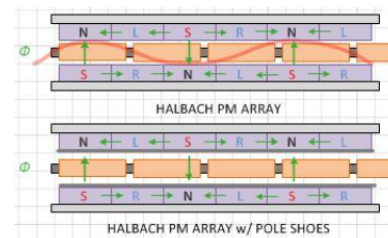


Figure 3: Halbach Array [3]

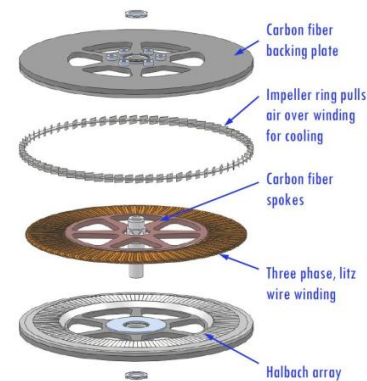


Figure 4: Halbach Motor Configuration [4]

As can be seen in the figures above, the current push to efficiently electrify what is done with fossil fuels or low-grade electric machines has caused a renaissance of alternative motor topologies. These topologies typically evolve from the traditional Radial Flux Permanent Magnet designs.

An emerging technology, which uses a very different magnetic machine topology, will be presented and discussed in this paper. This unique topology is called a Transverse Flux motor or machine. This motor fits under the DC or AC Brushless Permanent Magnet classification. This technology, unlike many new magnetic machine designs, has a broader market appeal in comparison to other recent topology directions.

RADIAL FLUX MOTOR TOPOLOGY

First some background on radial flux permanent magnet motors which dominate the automation and high performance Light Electric Vehicle (LEV) market.



Figure 5: Radial Flux Motor [5]

Brushless Permanent Magnet motors of the Radial Flux design have been commercially viable since 1962. [6] This 50 year history has resulted in well-developed computer models and readily available software packages which can design and analyze almost any radial flux configuration imaginable.

The flux path of the radial flux motor is well understood and is shown in Figure 6: below.

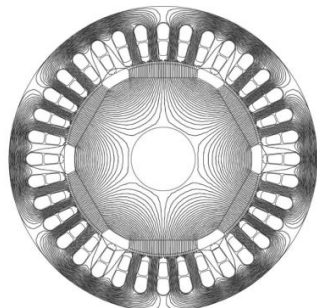


Figure 6: Radial Flux Magnetic Flux Path [7]

This type of motor design relies on wrapping the copper coils around stator teeth along the motors axial direction of rotation. These motors require a back iron on the stator to provide a return path for the coil induced magnetic field, and on the rotor to provide the return path for the motor magnetic poles.

Losses in these motors typically result from small gauge wire, end turns, and low coil packing density. Due to the low pole count associated with these motors, high efficiency is only achieved at high rpms. This normally results in additional transmission components between the motor and work actually being performed resulting in a lower overall system efficiency as compared to a direct drive system.

Even with these deficiencies this topology has been the major contributor to the advancement of light electric vehicles, hybrid car development, and industrial machinery. This technology powers more and more of our everyday electronic devices like cordless drills and major appliances. The radial flux motor design, in small power levels overcomes the traditional low efficiency induction motor designs which previously dominated many markets.

TRANSVERSE FLUX MOTOR TOPOLOGY

The Transverse Flux motor topology is not new; in 1885 W. M. Morday applied for a patent on the topology for alternators. [8] From a technology development standpoint, Transverse Flux machines have not made significant advances until the last 3 years. These recent advances have brought an esoteric motor technology into the realm of commercially viable.

The basic electromagnetic design breaks from traditional Radial and Axial Flux designs by putting the working flux in a different plane than is normally used. See Figure 6 for a traditional Radial Flux motor magnetic path. Compare this to Figure 7 for the Transverse Flux motor magnetic path.

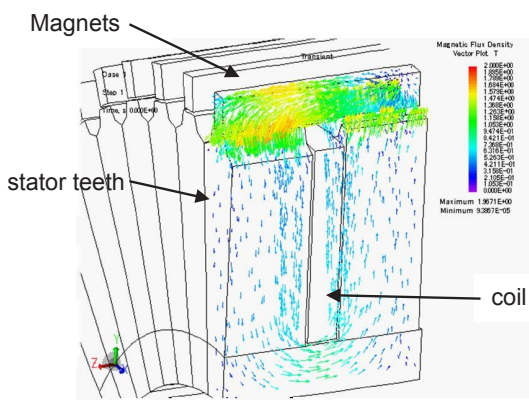


Figure 7: Transverse Flux Magnetic Flux Path [9]

Transverse flux motors benefit from the ability to achieve torque constants which are higher than traditional motor topologies. This is made possible by their unique configuration of coil shape, placement and relationship to motor stator teeth. The coil of a transverse flux motor can be wound circumferentially around the stator in a series of single loops.

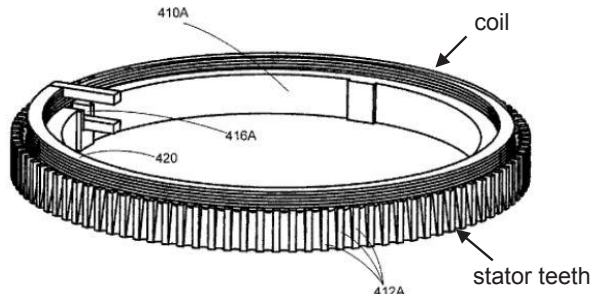


Figure 8: Transverse Flux Coil Location [10]

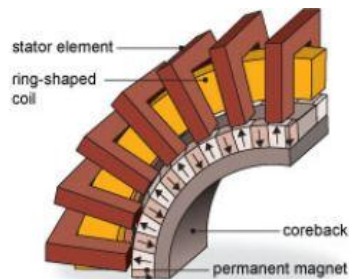


Figure 9: Transverse Flux Coil Configuration [11]

Not only does this make the process of winding coils easier, it allows for high fill or packing densities with large gauge flat wire. This drastically reduces coil I^2R losses, one of the major motor inefficiency contributors.

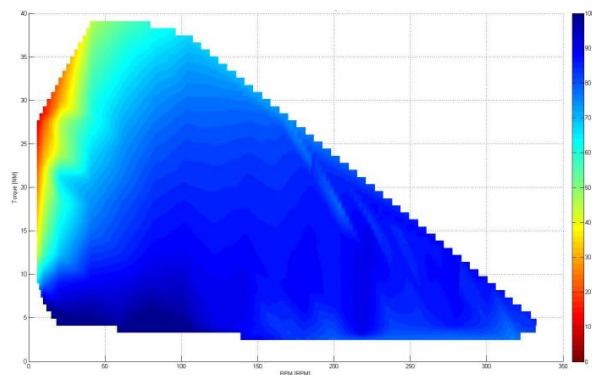


Figure 10: Transverse Flux Low Speed Efficiency [12]

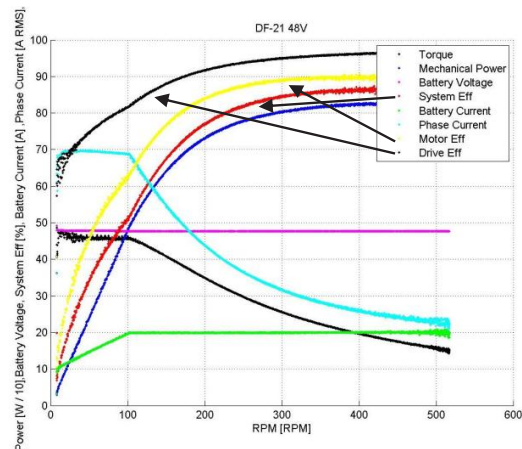


Figure 11: System Efficiency Map [13]

The placement of the coil in a transverse flux motor is circumferential on the stator, the number of stator teeth which translates into the number of possible motor poles, can be independently adjusted without changes to the motor coil. This allows the use of more magnetic poles than is generally found in other types of motors of the same frame size. Transverse flux motors tend to have low phase resistances, low phase inductances, and they tend to operate at relatively high commutation frequencies. To accomplish these characteristics the transverse flux motor design allows a decoupling of the copper winding path from the number of stator poles in a motor.

Increasing the pole count in a transverse flux motor does not change the total motor flux. The coil has not changed by increasing the pole count, nor has the total cross sectional area at any point along the flux conducting path. All that has been done is to dice our few flux paths, "pipes" into many smaller pipes with the same total area, "magnetic flow". Since the coil is unchanged, the magnetomotive force (mmf) is the same.

There is, however, a critical change in the motor's behavior. The electrical frequency has increased for any given speed because of the increase in motor poles. This in turn increases not the flux itself, but the rate of change of the flux reacting with the stator coils. Increasing the rate of change of the flux increases the B_{emf} of the coil. The increased B_{emf} increases the motor torque constant K_t, which allows a lower current to achieve a given torque. The lower current drops the I^2R losses, and the I (current) term is one of the dominate loss terms.

This same technique cannot be easily applied to radial flux motors. In the radial flux motor, the windings are changed by increasing the pole count. The pole count

can go up, but the mmf of the coils must be lower as a consequence. This in turn drops the B_{emf} of the motor even if the electrical frequency increases. When the B_{emf} is dropped, the motor torque constant drops proportionally, this then requires more current to achieve an equivalent motor torque of the same pole count when compared to transverse flux.

This magnetic tradeoff has advantages where a high pole count slow speed motor application is desirable. Transverse flux machines are not limited theoretically to this segment of the motor market, but research to determine if a lower pole count, higher rpm design has a competitive advantage needs more research.

A transverse flux design excels in two important motor performance areas, a high continuous torque to weight ratio, and high efficiency at low rpm. This makes the transverse flux motor ideal for direct drive motor applications. These applications range from direct drive semiconductor or flat panel manufacturing applications to Light Electric Vehicle traction motors.

One of the interesting benefits of the transverse flux motor design is in its ability to extend the continuous torque of a brushless motor beyond that of a radial flux design. The continuous torque of a motor almost always breaks down due to I^2R losses. When you increase the current in the motor to achieve higher torque, there is a limit to how long you can do this before thermal limitations come into play.

Increasing the current to the motor will increase the motor's torque, but also causes the motor to heat up faster. The low resistance and higher B_{emf} of the transverse flux motor allows for high continuous torques without suffering the same I^2R losses and stator heating.

The above differences are most apparent when comparing a radial flux motor's continuous and peak torque to a similarly sized transverse flux motor's continuous and peak torque. The transverse flux motor will have a significantly higher continuous torque capacity. A traditional radial flux motor will allow 20%-30% continuous to peak torque, a transverse flux motor will have 80%-85% continuous to peak torque. The peak torques of both motors will be similar, only the continuous torque capability changes.

This design difference is a result of several factors. A lower coil resistance decreases resistance losses at higher current levels. This advantage is the result of an increase in the wire gauge and packing density. The coils become rings of copper which is ideal for flat wire with a large cross section. The flat wire allows a tightly wound coil. This also improves the thermal characteristics of the copper coil.

On radial flux motors the limitation on wire gauge and slot fill density is a result of how effectively you can put wire thru the small slot between stator teeth. Once the wires are in the cavity the task of packing them effectively to achieve a high fill ratio is required. There are many manufacturers which use an automated process for this winding, but packaging density is still limited. In many applications the windings are hand installed which further reduces the packing density.

Another difference is the elimination of motor end turns and end turn management in a high copper fill motor. The end turns can add a significant amount of copper to a motor coil resulting in increased resistance but not contributing to motor torque. The single tightly wound coil of the transverse flux motor is not hindered by radial flux coil assembly and slot fill considerations. This decoupling of past design criteria simplifies the design and decreases resistance.

As discussed prior, the transverse flux high pole count improves a motor's continuous torque capability which when added to other base design enhancements results in a motor which runs cooler and is more effective at turning current into torque. This has been validated on transverse flux motors which run continuously within 80% of a comparable radial flux motor's peak torque [14].

The transverse flux motor does not have a higher peak torque compared to the radial flux motor, only the continuous torque number increases from a normal radial flux ratio of 20-30% of peak torque to the transverse flux ratio of 80-85% of peak torque. [14]

APPLICATIONS FOR THIS TECHNOLOGY

The characteristics of a transverse flux motor tie in well with low speed, high torque applications. If these applications are battery powered, the efficiency gain of the transverse flux design is an additional benefit. Testing performed in 2010 and 2011, demonstrated a 30 – 50% improvement in battery life over traditional radial flux motors. [14]

These benefits make light electric vehicles a strong candidate for transverse flux, as well as any industrial application which requires slow speed and high torque. Fluid moving and vertical axes without counter balances are examples of such applications.

TRANSVERSE FLUX DRIVE CONSIDERATIONS

In the case of transverse flux motors there are two main challenges facing a motor drive designer. The first challenge is the controllability of the current in the windings. The inductance of a transverse flux motor can tend to be anywhere from a few to several orders of magnitude lower than their traditional counterparts. As a result, higher PWM switching frequencies are generally

required for maintaining an acceptable amount of current ripple in the motor and drive for a given bus voltage.

As switching frequencies and current levels increase, the motor drive will create additional switching losses. The designer must pay special attention to the gate driving circuitry to ensure the devices are being driven into and out of conduction as quickly as possible, while at the same time ensuring that incidental $C \cdot dv/dt$ inducted “shoot-through” does not occur. Switches with small gate capacitances and low Rds-on values are critical for these sorts of drives.

The second biggest challenge relates to audible noise and vibration emitted from the motor while in operation. Since transverse flux motors deliver high torques at high commutation frequencies, cogging torque and torque ripple can yield excessive vibration and audible whine. This is especially true in the case of smaller motors with higher pole counts where manufacturing tolerance errors can come into play. Consequently, transverse flux motors can be very unforgiving when driven by traditional driving methods such as six-step or “trapezoidal” control. Instead more sophisticated current control methods must be employed such as sinusoidal or space vector PWM by means of field oriented control.

CONCLUSION

Although there is still a great deal of work needed to bring our understanding of Transverse Flux machines up to the level of Radial Flux machines the potential benefits will continue to drive this understanding forward. The rapidly changing green technology market will demand forever increasing motor and system efficiencies which in turn will drive further development on all motor topologies. Transverse Flux however is well on its way to becoming a technology of choice in several of these fields.

REFERENCES

- [1] Natural Resources Canada. oee.nrcan.gc.ca Energy Efficiency Reference Guide Electric Motors
- [2] ThinGap Ring Motor. www.thingap.com
- [3] Endless Sphere Technology. Endless-sphere.com Doing the Math. 2010
- [4] Launch Point Haulbach Motor. www.launchpnt.com
- [5] Servo Magnetics, Inc.
- [6] Brushless DC electric motor, Wikipedia Reference 2012
- [7] Emerald Institute. www.emeralinstite.com

- [8] Transverse Flux Motor, Wikipedia Reference 2012
- [9] Motor Excellence. Flux Path Technology Overview 2010
- [10] Motor Excellence. US Patent 2011/0169366 A1 2010
- [11] CalSol UC Berkeley Solar Vehicle. If we had cylinders we would be banging on all of them. calsol.berkeley.edu/news/2012
- [12] Motor Excellence. Edge Motor Efficiency Map 2011
- [13] Motor Excellence. Edge Motor Efficiency Map. Trust Automation Drive Efficiency Map 2011
- [14] Motor Excellence. Motor Testing Results when comparing best in class radial and axial flux electric bike motor technologies to transverse flux motors of comparable power. 2011

High-Speed Creation of Nanometer-Scale Features - Nanocoining

Thomas A. Dow, Erik M. Zdanowicz, W. John Nowak

Precision Engineering Center
North Carolina State University
Raleigh, NC

ABSTRACT

Microstructured surfaces have been made by diamond turning followed by plastic replication for many years. A variety of surfaces have been created for optical, chemical and mechanical applications. In optical applications, they are used for radiation management such as moving light from the source around the periphery of a laptop to the full viewing screen or creating inexpensive optical reflectors. In solar cells, they can assist in capturing light by reducing reflection. Mechanical applications can involve modifying adhesion, wetting and friction coefficient of a surface.

Extending this process to features smaller than the wavelength of light – nanostructured surfaces - has been problematic. For optical applications such as anti-reflective coating, a lithography process has been used but it is costly and slow. This paper describes a new approach to creating nanostructured surfaces using a process called Nanocoining. This is a method to rapidly transfer sub-micrometer features from a small, patterned die to a mold surface that can be used to create large areas of nanostructured surfaces. It could also be used to create features directly on small parts.

INTRODUCTION

Bio-inspired nanostructured surfaces are covered with nanometer scale features which, depending on their size and spacing, can produce valuable properties. Nanofeatures found on the surface of moth's eyes create an anti-reflective (AR) property which can serve as a defense mechanism for this nocturnal insect by blending the index of refraction from the air to eye surface. For nanofeatures to produce the AR property the period of the features must be less than the wavelength in the visible spectrum (380 – 750 nm). These types of surfaces can be useful in photovoltaic applications because of their abilities to perform over multiple wavelengths of light and large viewing angles. Structures found on the surface of the lotus leaf produce a superhydrophobic effect where water droplets sit on the surface with a very high

contact angle ($>150^\circ$). Water droplets roll off the leaf surface easily due to this high contact angle and pick up debris along the way to clean the surface. This property would also be attractive for photovoltaic cell coatings where build-up from operating in an outdoor environment is inevitable. While both properties are desirable, the main focus of this research has been in generating AR (optical) nanofeatures.

The use of nanostructured surfaces in consumer and commercial applications has become increasingly popular. The advantages of structured surfaces have been recognized and the demand for inexpensive coatings is high. The limitation of these nanostructured surfaces is the length of time required to produce a useable quantity. Current techniques for generating nanostructured surfaces have been successful but are not feasible because of long manufacturing times. Lithography methods are popular and can produce a limited area of high quality features, but suffer from a large number of manufacturing steps (spin coating, baking, etching...) as well as long duration (baking times can take 10 hrs).

A new process called Nanocoining was developed to address the limitation in production time. It uses a micro-scale diamond die with a nanostructured area attached to a high speed actuator to transfer the features to a mold surface. The mold surface (e.g. a drum) would be completely covered with features and then used to mass produce sheets of nanostructured surfaces. These sheets of nanostructures could be attached to surfaces depending on the property produced by the features. Areas of precisely indexed nano-indents have been created with nanofeatures exhibiting high fidelity using the nanocoining process.

PROCESS DETAILS

There are three main elements to the nanocoining process; 1) the diamond dies, 2) 2D actuator, and 3) precision lathe. The die was attached to a tool holder mounted to the end of an elliptical actuator which was mounted to the vertical axis of a 4-axis diamond turning

machine (DTM). The parameters of all three had to be carefully controlled to produce high quality indents.

Diamond Dies

The diamond die used in nanocoining had a $20 \times 20 \mu\text{m}$ area of nanofeatures. Each cone-like nanofeature was 330 nm wide at the base and 360 nm tall with a 160 nm radius at the tip. The spacing between features was 530 nm. An image of a die and the features can be seen in Figure 1.

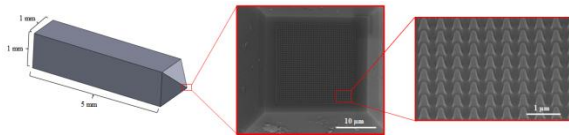


FIGURE 1. Diamond die used for nanocoining. This die has a $20 \times 20 \mu\text{m}$ nanostructured area with cone-like features.

To create AR surfaces it is critical that the spacing of the features on the die is less than the wavelength of visible light (380-700 nm). Because the property of the overall surface is dictated by the size and spacing of the features it would be possible to have a collection of dies which could be mounted on the actuator depending on the desired effect.

The features on the die shown in Figure 1 were machined with a Focused Ion Beam to the same shape as the desired features of the final surface. Therefore, this die would transfer its features (positive) to a mold surface by creating depressions on the surface (negative). The mold would then be used to create the final replicated part which would have features resembling the die's features (positive). Alternatively, the diamond die could be fabricated with depressions which would exhibit the negative of the desired final features. A die like this could be used to directly nanocoin a part with positive protruding features on its surface. Nanocoining features directly onto a surface could be attractive in scenarios where the nanofeatures need to be robust and would be the same material as the surface

Elliptical Tool-Path

Because the nanostructured area on the die is small ($1/5^{\text{th}}$ the diameter of human hair) relative to the desired total mold area, the indentation rate must be high. This also implies that the mold must constantly be moving since stopping and starting would slow the process. However,

a moving mold poses a problem to a traditional tool-path where the die is thrust into and out of the mold orthogonal to the direction of motion. If the die is pressed into a moving mold in this manner, the features will smear over a distance dictated by the mold speed and contact time. Smearing can not only distort the features transferred to the mold, but also cause material to become lodged in-between the nanofeatures on the die which further hampers the indenting process. In some severe cases, velocity mismatch between the die and mold (causing smear) has resulted in individual nanofeatures breaking away from the die face. Without the ability to match speed the indentation process will not work at high rates making the process ineffective.

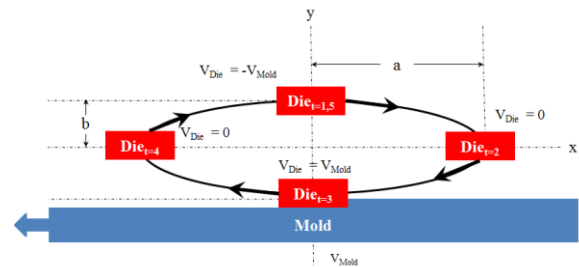


FIGURE 2. Elliptical tool-path definitions at various points in indentation cycle.

To avoid the issue of smear and match die and mold velocity it was necessary to introduce a second component of motion to the tool-path in the direction of the mold motion. There are a number of 2D tool-path shapes that can have simultaneous vertical and horizontal motion. The geometry chosen was an ellipse. An illustration of the tool-path used in the nanocoining experiments is shown in Figure 2.

An actuator designed for elliptical vibration assisted machining (EVAM) called the Ultramill was used to generate the elliptical tool-path. The Ultramill is a non-resonant actuator driven by two piezoelectric stacks kinematically coupled to a tool-holder and preloaded with a titanium diaphragm. When the two stacks are driven out of phase, a combination of extension and tilt produces an elliptical path. The shape of the path can be adjusted by varying the phase and amplitude of the AC drive signals. The correct phase angle and signal amplitude were found by using a two channel MTI Instruments photonic sensor to measure the motion of tool-holder. An acrylic cube was glued to the end of the tool-holder and covered with reflective tape as shown in Figure 3. The two light probes were

then mounted in a fixture which held them 90° apart and the motion was measured while varying the phase angle and signal amplitude. Figure 3 also shows multiple measurements taken with the photonic sensor at different amplitudes and phase angles that all produce an ellipse with the correct *a*-dimension. The ellipse used is indicated in Figure 3 and produces a nearly circular tool path.

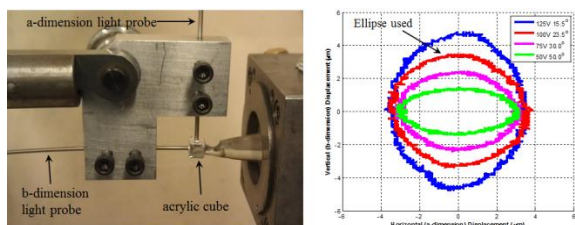


FIGURE 3. Measurement of Ultramill elliptical tool-path using MTI photonic sensors.

Alignment

Angular Alignment

One of the more challenging aspects to the nanocoining process is aligning the die with respect to the mold surface. The die must be aligned about three axes of rotation as shown in Figure 4(a). The coordinate system shown is that of the Nanoform DTM.

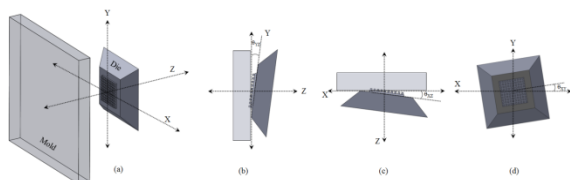


FIGURE 4. (a) Model of die with respect to mold, (b) Illustration of die misaligned in θ_{YZ} direction, (c) θ_{XZ} direction and (d) θ_{XY} direction

Any rotation of the die about the Y (θ_{XZ}) or X (θ_{YZ}) axes will cause the die to be tilted with respect to the mold surface. If the tilt is significant as shown in Figure 4(b) and 4(c) then a portion of the features will not contact the mold leaving a partial imprint. Based on the length of the structured area (20 μm) and the height of the nanofeatures (360 nm) an angular tolerance of 0.01° was chosen to ensure total transfer of features. A tilt error of 0.01° would produce a maximum height difference in nanofeatures of less than 4 nm.

An alignment fixture capable of rotating the die about the X and Y axes was built to compensate for tilt of the die. Initial indents were performed

to measure how much tilt was present. After examining the indents in an optical microscope, adjustments were made to the alignment fixture and more indents were created. This process was repeated until the Ultramill produced complete indents (entire indentation face has made contact) implying that the actuator had been aligned so that the die was parallel to the mold upon contact. Figure 5 shows some iterations of the alignment process.

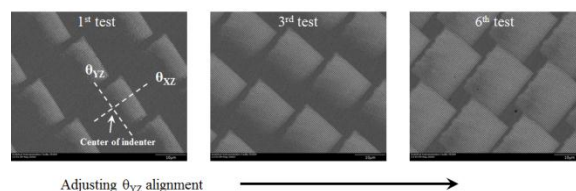


FIGURE 5. Iterations of angular adjustments. Features are completely present after 6th alignment test.

Linear Alignment

The location of each indent is related to 1) the die motion, 2) the peripheral speed of the part, 3) the cross-feed rate of the orthogonal axis, and 4) the orientation of the die. The goal is to overlap the die impressions but minimize this overlap region. Each of the parameters listed has a mean value and some variation as a function of time. For example, the peripheral speed of the part depends on the speed of the mold (for example the OD of a drum) as well as its diameter. Assuming a drum diameter of 318 mm, the circumference will be 1 m. Indenting at speed goal of 50 KHz with a 30 μm square die will require a rotational speed of 90 rpm. Since the nanofeatures are on the order of 250 nm, this will mean the speed control must be within 0.00025% to match the die edges within one row of features after one revolution. However, the features are placed in a spiral so the value of rotation speed is not as important as the change. The key is the die must move ahead within ± 1 row or out of 120 for a 30 μm die or 1.66%. This same accuracy will also be required for the cross-feed speed. This seems more reasonable. In addition, the diameter of the drum will vary as will the runout of the spindle that supports it. Clearly, the position control system will be challenging.

INDENTATION RESULTS

The nanocoin process was used to indent a 6 mm wide ring on a 1.25" diameter electroless nickel sample (stainless steel plated with nickel)

at a rate of 1 KHz. The ring started at a radius of 6 mm and ended at a radius of 12 mm resulting in an indented area of 339 mm². Based on this area and the area of the die the total number of indents was approximately 1.12 million created in 20 min. Once the part had been machined replicates were made using a UV curable material. An image of the indented part and replicates can be seen in *FIGURE 6*.

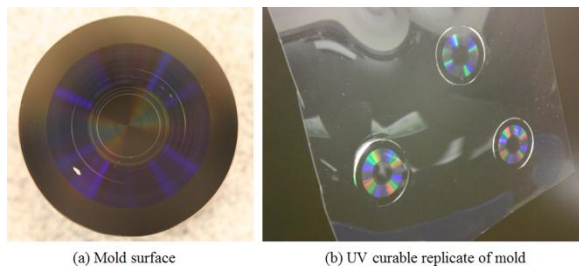


FIGURE 6. Nanocoined electroless nickel sample indented at 1 KHz (a) and replicates made from UV curable material (b).

The part and replicates shown in Figure 6 exhibit diffraction because the spacing of the features (500 nm) is not below the wavelength of visible light. Indents created using new dies with smaller feature spacing will avoid diffraction because their feature spacing will be less than the wavelength of visible light.

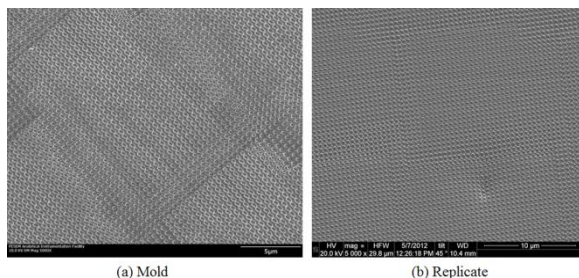


FIGURE 7. SEM image of nanofeatures mold and plastic replication.

The nickel plated mold in Figure 7(a) was measured in a scanning electron microscope (SEM). A similar image of the plastic replica from this mold is Figure 7(b). The areas in Figure 7 that appear to be the borders of the indents are overlapped regions which was done intentionally (2 μ m) to ensure total coverage of the mold. The overlapped sections resulted in areas which had a higher density of features because the area had been indented twice and was easily recognizable in the SEM images.

The nanofeatures shown in 7(a) were created with the die in Figure 1 so the shape is a conical indentation. Figure 7(a) shows mold material

sticking out of the surface around the hole with a higher aspect ratio than the typical pile-up caused by indentation.

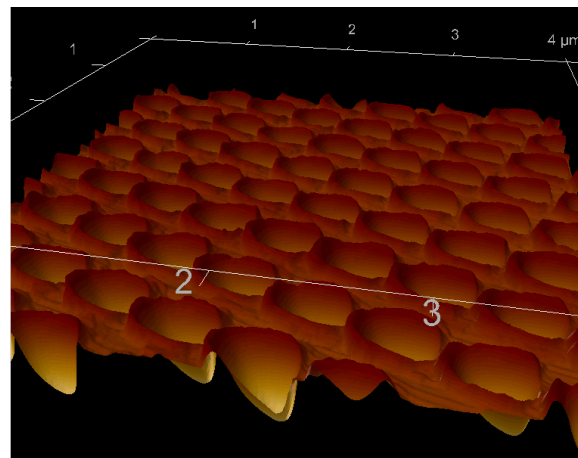


FIGURE 8. AFM image of EINI mold surface.

Figure 8 is an AFM image of the mold surface showing these pushed up features. Normal indentation would see the material pushed up and away from the feature but in this case it is a higher aspect ratio more like a chip. The origin of these features is not clear but they do not appear to be detrimental to the overall surface quality of the replicated surface. Note that the shape of the features in Figure 8 are not symmetric as is the die and may indicate the effect of speed mismatch between die and mold.

CONCLUSIONS

Large areas of sub-wavelength, nanofeatures have been created using a new process known as Nanocoining. A small diamond die (~ 30 μ m square or less than the thickness of a hair) has been FIB machined to form thousands of nanofeatures. This die was attached to a high speed actuator that has a 2D tool-path designed to match die and mold velocity to minimize smearing of the features. The die was aligned in multiple directions to ensure complete transfer of features and proper location of indents. The die was pressed into the mold in register to create features on a moving mold surface. The continuous features generated on the mold and replicated onto plastic sheet were high-fidelity reproductions of the original die feature shape.

ACKNOWLEDGEMENT

This work is supported by the NSF under Grant No. 1000055 monitored by Bruce Kramer.

MECHANICAL PATTERNING OF OPTICAL MICROSTRUCTURES

Ekkard Brinksmeier, Ralf Gläbe, Lars Schönmeyer and Axel Meier
LFM – Laboratory for Precision Machining
University of Bremen
Bremen, Germany

INTRODUCTION

Mechanical patterning by diamond machining is a fast and reliable way to manufacture optical microstructures in metal optics for direct use as well as in molds for replication of glass and plastic optics [1]. Depending on the generated geometry and structure size, these micro optical components can serve different purposes by incorporating refractive or diffractive functions. Typical applications for diamond machined optical microstructures are security holograms [2, 3], multi-focus Fresnel lenses [4] or display backlights [5]. The spectrum of machinable geometries however, is limited by the applied cutting kinematics. Processes such as turning are generally limited to rotational symmetric structures, while linear patterns can be generated by processes like fly-cutting or micro-grooving [6].

In this context, two novel diamond machining processes have been introduced lately. These are nano fast tool servo (nFTS) turning for the generation of diffractive optics as well as Diamond Micro Chiseling (DMC) for generating prismatic microstructures.

This paper will give a short overview on the basic principles of these processes and assess their applicability for supporting the semiconductor industry.

NANO FAST TOOL SERVO TURNING

Diamond turning is a precise and fast process to machine freeform and microstructured surfaces [3, 7]. By combining a common diamond turning process with a so-called nano Fast Tool Servo (nFTS), the spectrum of machinable geometries is extended to diffractive microstructures. Such structures serve as diffractive optical elements (DOE), which are capable to shape an incident laser beam. Novel applications are reflective phase masks for ultra-violet (UV) lithography.

Machining process and structure generation

The microstructure is generated by a modified diamond turning operation. For machining of

non-rotationally symmetric diffractive microstructures a nano Fast Tool Servo (nFTS) is integrated in the machine tool. The nFTS is a piezo actuator, which adjusts the tool position perpendicular to the workpiece surface. Thus, the depth of cut is modulated in a range up to $z^* = 350$ nm at a maximum frequency of 10 kHz. Due to low hysteresis of the piezo ceramic, deviations of the nominal stroke are in the order of 4 nm, which allows for an open-loop operation. By this highly dynamic tool movement, the spiral tool path of the face turning process is superimposed with a microstructure, consisting of 2,000 segments (pixel) per revolution (cf. FIGURE 1).

Height and position of each pixel are specified by the optical design. Specifically developed algorithms are applied to calculate the structure data [8]. Initially, the structure data are calculated in Cartesian coordinates and subsequently fitted to the spiral tool trajectory. To ensure a precise positioning of each pixel in axial and radial direction, the encoder signal of the main spindle triggers the nFTS modulation.

For the manufacturing process monocrystalline diamond tools with a specific geometry are used. The tools feature a tool cutting edge angle of $\kappa = 6^\circ$ and a clearance angle of $\alpha = 20^\circ$ as depicted in FIGURE 1. Tool geometry combined with the process kinematics results in spiral shaped, blazed structure, which is characteristic for this process. The diffractive microstructure is capable of modulating the phase of an incident wavefront and shape a laser beam into arbitrary but defined intensity distributions.

The functionality of the DOEs, and consequently, the quality of the holographic reconstruction is influenced by several aspects. Besides the optical design, the mechanical components such as machine tool, nFTS and diamond tools are crucial for achieving a high precision that meets optical demands. Additionally, the achievable accuracy is strongly influenced by the workpiece material. For

application in the visible spectrum at a wavelength of $\lambda = 632 \text{ nm}$ nickel silver was identified as a suitable material, due to the low roughness of $S_a = 5 \text{ nm}$ on the flanks of the blaze structure, a good structure accuracy and only minor burr formation [9].

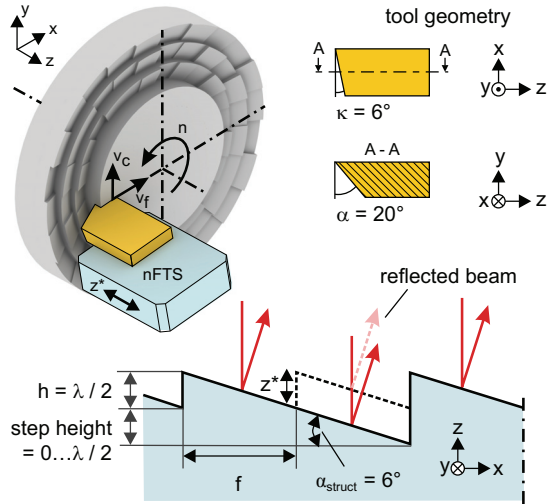


FIGURE 1. Process principle for generating diffractive optical elements.

Novel applications of the DOEs are phase masks for UV-lithography to illuminate photo-sensitive surfaces in defined patterns. Applying UV radiation with wavelengths below 355 nm requires a precise machining and also a high reflectivity of the used workpiece materials.

Investigation of workpiece materials

Workpiece materials applied for machining of UV-DOEs have to meet optical requirements in terms of high reflectivity and yield a precise structure accuracy. For this purpose several materials commonly used for diamond machining were investigated regarding their UV-reflectivity. UV-reflectivity of nickel silver, copper, nickel-phosphorous platings and aluminum was measured by a UV-sensitive photodiode for different wavelengths. For nickel silver the highest reflectivity measured 46% at 355 nm and decreased for lower wavelength down to only 20% at 193 nm. Copper and nickel-phosphorous showed similar reflectivity, which are not sufficient for exposing photosensitive surfaces. Aluminum has a theoretic reflectivity in the UV-range of approximately 90%. To achieve a high reflectivity a pure aluminum Al1070 (Al > 99.7%) with an ultra fine grained (UFG Al) structure was selected, which is fabricated by a specific extrusion process [10]. Measurements

showed a reflectivity around 80% at wavelengths from 248 nm to 355 nm and 60% at 193 nm.

The UFG aluminum is diamond machinable in sufficient quality, which was verified in turning experiments with diamond radius tools leading to a surface roughness of $R_a < 4 \text{ nm}$ [11]. In order to investigate its suitability for machining of blazed gratings further cutting experiments were conducted. For reasons of comparability conventional aluminum Al7075 was machined additionally.

Blaze gratings were diamond turned using the cutting parameters given in FIGURE 2. The surface topography was analyzed by confocal microscopy and atomic force microscopy (AFM) measurements. Both materials show a good structure accuracy with deviations of the structure angle $\alpha_{\text{struct}} = 6^\circ \pm 0.2^\circ$. For UFG Al a slight burr formation can be detected on the edges of the structure. As an important optical property the surface roughness was measured on the flanks of the structure. The average roughness S_a measures 7 nm for UFG Al and 10 nm for Al7075. The confocal images show minor defects of the Al7075 surface, whereas for UFG Al a homogenous structure was achieved.

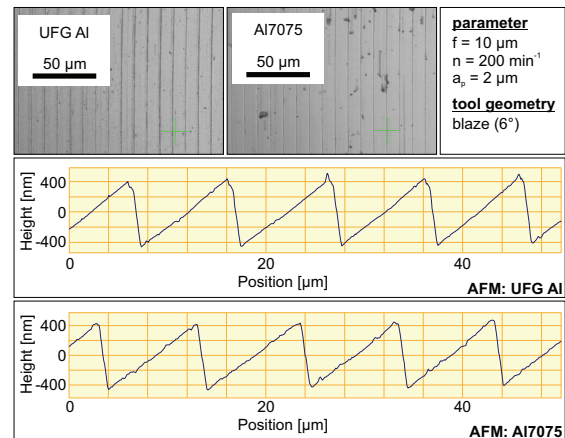


FIGURE 2. Confocal and AFM measurement of diamond turned blaze structure.

Due to its high reflectivity, low surface roughness and better homogeneity of the blaze structure UFG Al was applied for machining of diffractive phase masks.

Diffractive phase masks for UV-lithography

Functionality of the diamond turned phase masks was assessed in an optical setup. A test image was designed to examine the quality of

the optical reconstruction consisting of different elements including gray scales, lettering, a Siemens star and several checkered patterns with differing resolutions (cf. FIGURE 3). For the image the corresponding structure was calculated and diamond machined using UFG AI. A microscopic image of the structured DOE surface is shown in FIGURE 3 exhibiting separate pixel with different height levels.

The machined structure was illuminated with UV-radiation at a wavelength of 325 nm in an optical setup. The incident beam is reflected on the structured surface which modulates the phase. Using a beam splitter and focusing lens enables to project the beam onto a reconstruction plane, where the intensity distribution of the reconstruction was measured by a UV-sensitive CCD camera. All graphical elements (gray scales, Siemens star, checkered patterns) show smooth edges and are distinctly separated, which validates the general functionality of the phase mask. Also, the lettering is displayed clearly. The squares of the checkered patterns have varying edge lengths between 1 and 16 pixels. However, only the patterns with 16 pixel edge length can be distinguished.

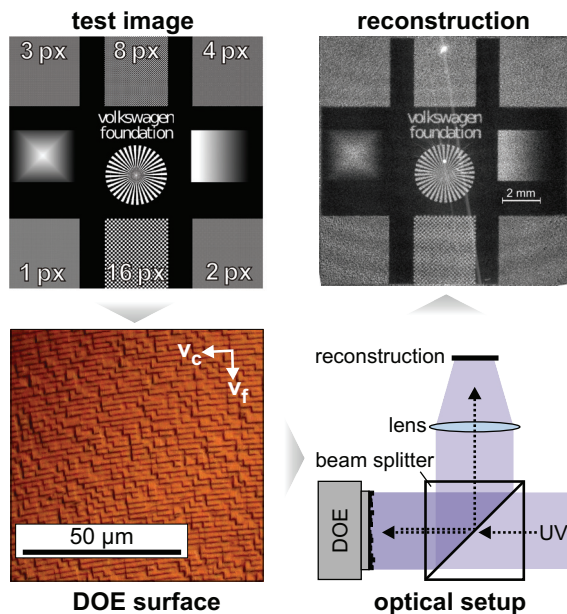


FIGURE 3. Assessment of diamond turned phase masks by UV-exposure.

DIAMOND MICRO CHISELING

Even with the addition of a fast tool servo, the geometric spectrum of standard machining processes like turning or milling is strictly limited, when it comes to the generation of prismatic microstructures with defined sharp edges. Thus, the Diamond Micro Chiseling (DMC) process has been developed, allowing the machining of prismatic micro optics, such as pyramidal cavities and V-grooves, in sizes (cf. FIGURE 5) between 50 and 500 µm.

Diamond tools

The DMC process relies on a specifically designed V-shaped monocrystalline diamond tool (see FIGURE 4). The opening angle of $\delta \approx 50^\circ$ and the corner angle of $\varepsilon < 70^\circ$ determine the geometric spectrum of the machinable microstructures (i.e. maximum structure angle and number of facets). For improving the cutting behavior and wear resistance of the tool, intrinsic rake ($\gamma \approx 22^\circ$) and clearance ($\alpha \approx 2^\circ$) angles as well as a rounded tool nose ($r_\delta = 1-12 \mu\text{m}$) were incorporated in the design.

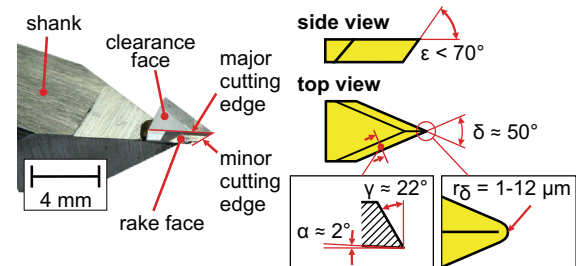


FIGURE 4. V-shaped diamond tools for DMC.

Process kinematics

Utilizing these tools, each facet of such a structure is machined separately by moving the tool on a triangular or trapezoid tool path through the substrate (cf. FIGURE 5).

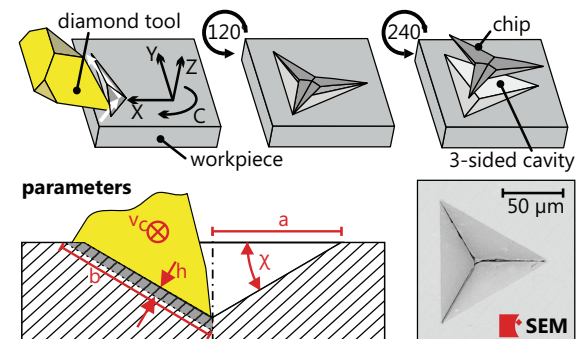


FIGURE 5. Kinematics, process parameters and exemplary structure for DMC.

The inclination angle of the tool (χ) is directly copied to the structure and determines its reflective functionality. In order to minimize the stress on the applied diamond tools, a constant undeformed chip thickness (h) is applied by cutting the desired structure in multiple layers, gradually increasing its size.

Tool alignment

It is essential for the feasibility of the cutting kinematics that after rotating the workpiece, the diamond tool is positioned to the endpoint of the previous cut. Thus, the diamond tool has to be aligned in all linear axes of the applied machine tool with a precision of $<1 \mu\text{m}$.

Additionally, the inclination of the diamond tool has to be set with $<0.1^\circ$ precision for obtaining high-performance optics as it determines the reflective behavior. Due to the fragile nature of the diamond tools, this cannot be measured directly on the tool using contact probes. Furthermore, the resulting structure angle cannot be directly measured at higher slopes. Thus, the tool is aligned parallel to a reference plane in the first step. The remaining tilt can then be measured precisely via interferometry (see FIGURE 6) and is compensated for by using the B-axis of the ultraprecision machine tool.

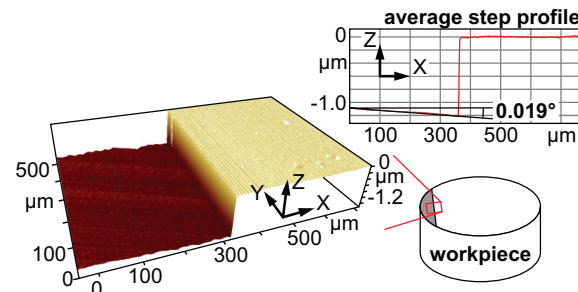


FIGURE 6. Angular tool alignment by interferometric evaluation of step profile.

After setting the diamond tool to the desired inclination angle, the diamond tool tip is aligned to the rotational center of the workpiece by cutting distinctive microstructures, measuring their shape using a calibrated high-resolution video microscope and determining compensation values for the tool's position.

Machinable substrate materials

Most diamond machinable materials can be microstructured by using DMC. However, best results have been achieved with electroless nickel (NiP), nickel silver CuNi18Zn19Pb1 (N37)

or ultra fine grained aluminum Al1070 (UFG Al) samples. The results for three sets of parameters applied on the abovementioned substrate materials are shown in FIGURE 7.

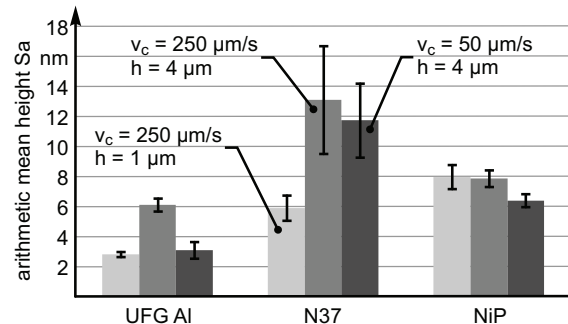


FIGURE 7. Arithmetic mean height S_a of facet flanks for commonly utilized substrate materials.

While electroless nickel is more or less insensitive to changes in the process parameters, it can be seen that a small undeformed chip thickness (h) and a low cutting speed (v_c) are the critical factors for achieving an optical surface finish ($S_a < 10 \text{ nm}$) on nickel silver N37 and UFG aluminum.

Applications

The structures machinable by DMC can be superimposed to generate functional patterns such as retroreflective arrays or novel types of light guides (e.g. micro beam splitter) in LED optics. FIGURE 8 shows an example of a nickel silver molding insert for the replication of corner-cube retroreflectors.

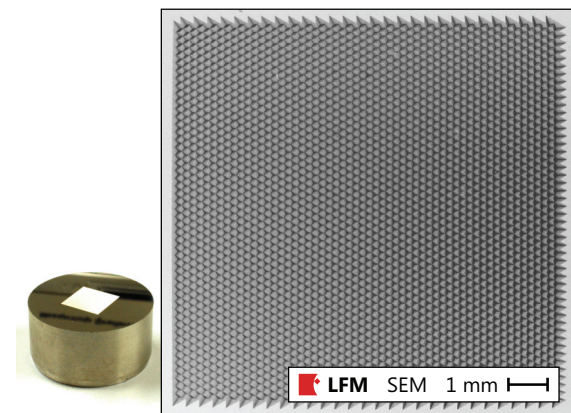


FIGURE 8. $10 \times 10 \text{ mm}^2$ retroreflective array machined by DMC.

This pattern contains 5,304 triple mirror elements with $150 \mu\text{m}$ aperture size on an area of $10 \times 10 \text{ mm}^2$. The total machining time for this pattern was approximately 95 h.

CONCLUSION

In this paper, two novel diamond machining processes have been presented, which extend the spectrum of machinable microstructures to diffractive optics as well as discontinuous prismatic shapes. These structures can be used to generate functional surfaces on a micro and nano scale and thereby opening up new possibilities for the semiconductor industry, e.g. for UV-lithography or alignment measurement.

Diffractive microstructures can be machined by a modified diamond machining process, in which the depth of cut is modulated by a nano Fast Tool Servo. The microstructures serve as diffractive phase masks for UV-lithography and require suitable workpiece materials. Criteria for selection of workpiece materials are a sufficient reflectivity in the UV-spectrum and diamond machinability in optical quality. The requirement of reflectivity is best met by aluminum achieving a reflectivity of around 80% at wavelength from 248 to 355 nm. Two aluminum alloys, ultra fine grained Al1070 and conventional Al7075, were investigated regarding their machinability. UFG Al showed the best results with an average roughness of $S_a = 7$ nm and a good homogeneity of the machined microstructure. The diffractive phase masks were exposed by UV-light and the intensity distribution was measured, showing a good quality of the optical reconstruction. Future research will focus on increasing the diffraction efficiency by reducing the global form deviation of the phase masks.

The Diamond Micro Chiseling (DMC) process can be used to machine discontinuous prismatic structures. It has been shown that using the DMC process, an optical surface finish can be generated on the facets of these microstructures with various substrate materials. However, very low undeformed chip thicknesses and cutting speeds have to be applied. Several of these microstructures can be superimposed to generate functional pattern, such as retro-reflective arrays with a structure size of 150 μm . Future research will concentrate on the application of the DMC process to curved surfaces, such as drums for roll-to-roll replication processes.

ACKNOWLEDGEMENT

The authors like to thank the Volkswagen Stiftung for funding the work on the nano Fast Tool Servo and the Deutsche Forschungs-

gemeinschaft for funding the work on Diamond Micro Chiseling.

LITERATURE

- [1] Bruzzone AAG, Costa HL, Lonardo PM, Lucca DA. Advances in engineered surfaces for functional performance. *CIRP Annals*. 2008;57(2):750-769.
- [2] Mahalik NP, Lee RA. Micromanufacturing for Document Security: Optically Variable Devices. *Micromanufacturing and Nanotechnology*: Springer Berlin Heidelberg; 2006. p. 131-169.
- [3] Li L, Yi AY, Huang C, Grewell DA, Benatar A, Chen Y. Fabrication of diffractive optics by use of slow tool servo diamond turning process. *Optical Engineering*. 2006;45(11):113401-113409.
- [4] Takeuchi Y, Maeda S, Kawai T, Sawada K. Manufacture of Multiple-focus Micro Fresnel Lenses by Means of Nonrotational Diamond Grooving. *CIRP Annals*. 2002;51(1):343-346.
- [5] Brecher C, Schmitt R, Lange S, Koerfer F, Niehaus F, Widemann R. Großflächige Mikrostrukturierung. *wt online*. 2006;96(5):276-280.
- [6] Brinksmeier E, Gläbe R, Schönmann L. Review on diamond-machining processes for the generation of functional surface structures. *CIRP J Manuf Sci Technol*. 2012;5(1):1-7.
- [7] Lu XD, Trumper DL. Ultrafast Tool Servos for Diamond Turning. *CIRP Annals*. 2005;54(1):383-388.
- [8] Dankwart C, Falldorf C, Gläbe R, Meier A, Kopylow Cv, Bergmann RB. Design of diamond-turned holograms incorporating properties of the fabrication process. *Appl Opt*. 2010;49(20):3949-3955.
- [9] Brinksmeier E, Riemer O, Gläbe R, Lünemann B, Kopylow Cv, Dankwart C, Meier A. Submicron functional surfaces generated by diamond machining. *CIRP Annals*. 2010;59(1):535-538.
- [10] Olejnik L, Kulczyk M, Pachla W, Rosochowski A. Hydrostatic extrusion of UFG aluminium. *International Journal of Material Forming*. 2009;2(0):621-624.
- [11] Osmer J, Riemer O, Brinksmeier E, Rosochowski A, Olejnik L, Richert M. Diamond turning of ultrafine grained aluminium alloys. 7th euspen International Conference; 20.-24.05.; Bremen, Germany; 2007. p. 316-319.

High Performance Motion And Vibration Control for Precision Machines

Tsu-Chin Tsao, Yigang Wang, Kevin Chu
Mechanical And Aerospace Engineering Department
University of California Los Angeles
Los Angeles, California, United States of America

ABSTRACT

Precision requirement of semiconductor manufacturing and inspection machines has become more and more stringent as feature size of integrated circuit continues to decrease. Mechanical vibration induced by the operation of the machines and accessory equipment has become a critical issue for both manufacturing and inspection. Passive vibration isolation from environmental sources is necessary and effective but this approach cannot address in-situ disturbance sources, such as motion induced vibration, fan/pump noise, air flow turbulence, etc. Active control is required to minimize the effect of these disturbances. In this paper we discuss advanced control approaches, which are effective in rejecting disturbances with various dynamic characteristics.

CONTROL FOR DETERMINISTIC DISTURBANCES

The mechanical vibration sources in precision machines can be loosely classified in two categories. The first category is of deterministic characteristics, where the disturbances can be modeled as signals generated as the free response of a stable or marginally stable dynamical system with some initial conditions. Such type of disturbances can physically be harmonic or periodic disturbances coming from rotating devices such as fans, pumps, or gear trains, noise or vibration appearing as impulse response from mechanical contact of two moving parts, and etc. Further, 60-Hz disturbances from AC power sources are quite common even with exhaustive effort in isolation and shielding.

The underlying dynamical system and its initial condition may be known a priori, partially known, or otherwise uncertain or changing from time to time. Active control to compensate for such type of disturbances depends on the a priori knowledge and uncertainty.

As a well known principle, feedforward control is used to cancel disturbances with a priori known characteristics while feedback control action is used when uncertainties exist. For example, generating pre-specified trajectories can be formulated as equivalent to rejecting a priori known disturbances. As such feed-forward control optimized for performance under such practical constraints as speed and acceleration limits is particularly useful [1].

Asymptotic regulation can be achieved when the disturbance dynamics are placed the feedback path of the feedback control loop. This is the celebrated internal model principle. For example, when the frequency of a harmonic disturbance is known but the magnitude and phase are unknown or uncertain, the internal model principle based controller is particularly effective. When the frequency is uncertain, adaptive filtering can be applied to on-line identify the frequency [2].

CONTROL FOR RANDOM DISTURBANCES

The second category of disturbances is of random nature. Thermal noise in electronics, air turbulence in machines, and quantization and finite word length effects are unavoidable sources of random disturbances in most precision systems.

The aggregated effects of random disturbances are usually modeled as a stationary stochastic process, where the disturbance is generated by filtering a Gaussian white noise. When the filter dynamics are given, a linear feedback controller can be designed to achieve minimum output variance. In practice, the filter dynamics are unknown or varying. Adaptive control methods that on-line identify the stochastic process dynamics and minimize the output variance are particularly useful for compensating random disturbances.

EXAMPLES of INTEGRATED CONTROL SYSTEM AND EXPERIMENT

Both deterministic and random disturbances exist in most precision machines therefore control system must integrate the aforementioned specific control methods for particularly type of disturbances [2-6]. One example of the integrated control is shown in Figure 1, which contains an adaptive control Q and adaptive internal model control, which changes with the on-line identified harmonic disturbance frequencies ω .

The high performance control of the integrated control is illustrated by experimental results on controlling an in house made Halbach linear motor, which is supported by an air bearing slide and the positioning sensing is from a 4 micron period sinusoidal encoder (Figure 2) [3]. The system has an inherent 60 Hz disturbance. Furthermore, a rotary motor which rotates at about 75 Hz is placed on the linear motor slide. Thus the linear motor is subject to mainly 60 and 75 Hz harmonics and random disturbances. Figure 3 and Figure 4 show the experimental results respectively for PID control only, PID with adaptive minimum variance control, and PID, with adaptive minimum variance control and adaptive internal model. The RMS values of the output errors for these three experimental cases are respectively, 47.5, 25.3, 9.5 nm. The adaptive minimum variance control action effectively reduces output errors over PID control for broad low frequency range for a little more than 100 Hz. The adaptive internal model control adaptively identifies the two most prominent harmonics and locks itself on cancelling the harmonics at 60 and 75 Hz.

More detailed description and discussion will be provided in the extended abstract and presentation.

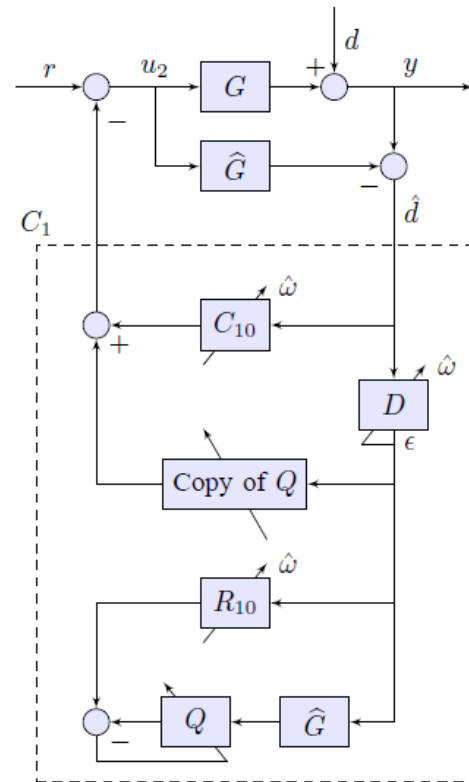


FIGURE 1. Adaptive control with adaptive internal model.

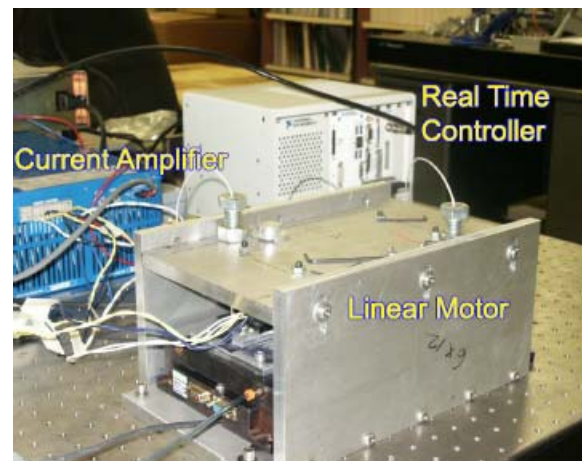


FIGURE 2. Experimental System: Halbach Linear Motor

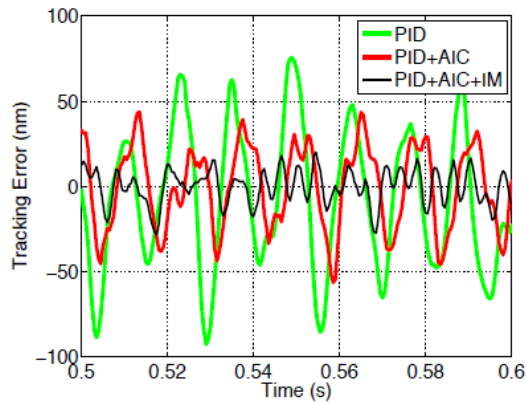


FIGURE 3. Linear motor output errors with PID control, PID + Adaptive Control, and PID + Adaptive Control + Adaptive Internal Model, respectively

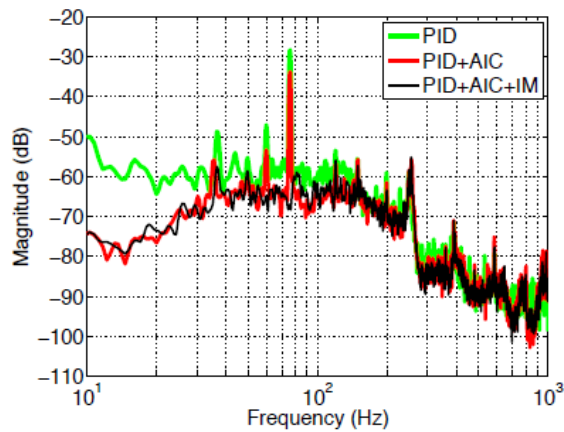


FIGURE 4. Power spectral density of time traces in Figure 3

REFERENCES

- [1] Tsao, T. C. , "Optimal Feed-Forward Digital Tracking Controller Design," ASME Journal of Dynamic Systems, Measurement, and Control, 116, 583-592, 1994.
- [2] Wang, Yigang, Chu, Kevin, Tsao, Tsu-chin, "Adaptive Rejection of Stochastic and Deterministic Sinusoidal Disturbances with Unknown Frequency," 2009 American Control Conference Hyatt Regency Riverfront, St. Louis, MO, USA June 10-12, 2009, p 5641-5646
- [3] Yigang Wang, Kevin C. Chu and Tsu-Chin Tsao, "Analysis and Control of Halbach Linear Motor for Nanopositioning," Proceedings of the ASME 2009 Dynamic Systems and Control Conference DSCC2009 October 12-14, 2009, Hollywood, California, USA. DSCC2009-2765, p1-8.
- [4] Yigang Wang, Kevin C. Chu and Tsu-Chin Tsao, "Adaptive Control for Deterministic Trajectory Tracking and Random Disturbance Rejection With Application to Nano-Precision Positioning of a Halbach Linear Motor," Proceedings of the ASME 2009 Dynamic Systems and Control Conference DSCC2009 October 12-14, 2009, Hollywood, California, USA. DSCC2009-2776, p1-8.
- [5] Yigang Wang, Kevin C. Chu, Herrick L. Chang and Tsu-Chin Tsao, "Laguerre Based Adaptive Control of Piezoelectric Actuator for Nanopositioning," 49th IEEE Conference on Decision and Control, December 15-17, 2010 Hilton Atlanta Hotel, Atlanta, GA, USA, p 3712-3717.
- [6] Kevin C. Chu and Tsu-Chin Tsao, "Enhancing Transient Response of Asymptotic Regulation with Disturbance Onset," 2011 American Control Conference on O'Farrell Street, San Francisco, CA, USA 588-593, June 29 - July 01, 2011, p5388-5393.

COORDINATING DIGITAL I/O WITH PRECISION MOTION

Curtis S. Wilson
Vice President of Engineering
Delta Tau Data Systems, Inc.
Chatsworth, CA USA

INTRODUCTION

As demands for increased precision in motion control systems, such as those for semiconductor fabrication and test, combine with the need for increased throughput, the requirements for tightly synchronizing inputs and outputs to motion are increasing, particularly for digital I/O accessed “on the fly”, during motion. Precision controllers are providing increasingly sophisticated hardware solutions to this synchronization issue, coupling I/O to measured position values much more tightly than software-based solutions can do. Recent improvements in “position capture” input circuits and “position compare” output circuits are yielding very small resulting errors compared to earlier strategies, permitting new capabilities in speed/accuracy combinations. Operations that formerly required a stop-and-settle period can now often be performed during motion.

BACKGROUND

Early digital motion controllers provided only software linkage between position values and discrete I/O. In many cases, the I/O was tied to commanded, not actual position, which made the servo error part of the error budget. Even when checked against actual position, the obvious limitation of this technique was the potential time delay introduced by the limited software scan rate. This delay multiplied by the axis speed introduced a minimum level of potential error. Interrupt-based software techniques could offer some improvement, but retained significant reaction time and often could not access an instantaneous position value.

For this reason, hardware-based techniques implemented in digital logic have developed over the last 25 years to improve the linkage between position and discrete I/O. Implemented in digital logic ASICs, these are broadly divided into two types of circuits: “position capture” circuits that latch the position value immediately on receiving an input, and “position compare” circuits that create an output when the measured position reaches a preset value.

Over the years, the capabilities of these circuits have improved, increasing their speed and effective resolution. This paper analyzes the evolution of these functions, evaluating the capabilities of several generations, culminating in today’s state-of-the-art circuits.

BASIC CAPTURE AND COMPARE CIRCUITS

The early hardware-based position-capture and compare circuits provided a great improvement over software-based techniques, but were limited compared to today’s expectations. The improvement was fundamentally due to the fact that the interface circuitry updated at a clock frequency measured in megahertz, while the software updates were measured in kilohertz.

All aspects of this circuitry needed to be updated at the high (MHz) rate for this to be useful. In practice, this meant that these circuits were used for incremental digital encoders feeding a high-frequency counter. The value of the counter could be “captured” within a hardware clock cycle on the detection of an edge of a digital input, and checked against a preset “compare” register value each cycle, setting an output when the values matched.

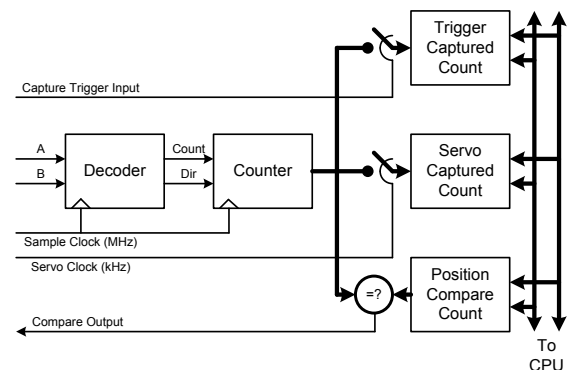


FIGURE 1. Incremental encoder processing circuitry for servo position feedback with hardware capture and compare

There are two key limits to the accuracy of these circuits: the position resolution and the time resolution. The position resolution is the discretized “count”, and the time resolution is the hardware sample clock period. This time period multiplied by the velocity yields a position uncertainty in the relationship that is added to the discretized resolution uncertainty.

WORKING WITH OTHER DEVICE TYPES

Because these circuits work by immediate access to a high-frequency counter, they cannot be used directly with feedback devices that are not processed in this way, such as parallel-data interferometers and serial encoders. There are a couple of techniques that are useful for these sensors that have low-frequency access.

Timer-Assisted Software Capture

The first technique can be called “timer assisted software capture”. In this technique, the sensor position is only obtained on a low-frequency (kHz) synchronous clock. The capture trigger latches a high-frequency hardware timer that has been reset to zero on the most recent sensor-sampling clock. Software then interpolates between the most recent two position samples based on the timing of the trigger. In this technique, any delay (time offset) between the latching of the sensor position and its availability to the controller, as with a serial encoder, must be included in the calculations. Note that this technique does not provide any fast compare capabilities.

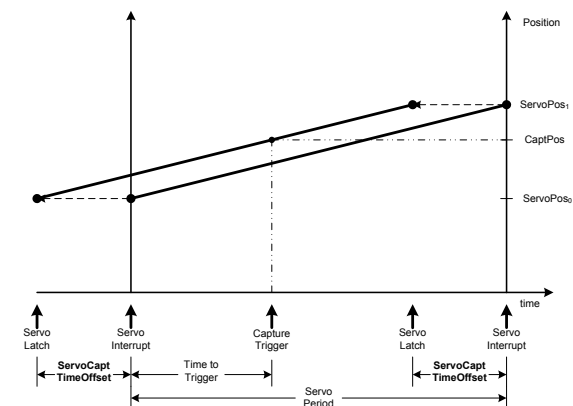


FIGURE 2. Timer-assisted software capture analysis. Trigger-captured position calculated from consecutive servo positions and trigger time.

Tracking Loop with Simulated Count

Another strategy is to track the position from such a sensor with a simulated software/hardware loop of the type that is commonly used to control traditional “pulse-and-direction” stepper drives. A pulse-frequency-modulation circuit feeds a high-frequency counter that is used to close a feedback loop that attempts to keep the counter value as close to the sensor position as possible. The high-frequency counter can be used with hardware capture and compare circuits just as if it were driven from a physical incremental encoder. While this technique provides very significant improvement in the tightness of coupling of I/O to position, the quality of the coupling is potentially limited by imperfections in the tracking loop. Typically, the added errors are negligible in precision systems.

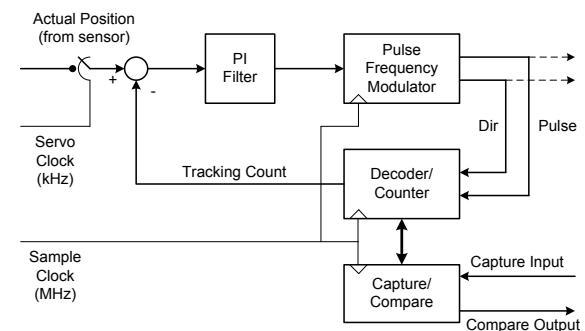


FIGURE 3. Tracking loop with hardware counter and capture/compare capabilities

SINUSOIDAL ENCODER ISSUES

Sinusoidal encoders have become increasingly popular in high-precision applications, providing the highest resolutions and accuracies available at reasonable cost. Processing the analog signals to provide a high number of states per line has required high-resolution A/D converters that (until recently at reasonable cost) could not be sampled at the required Nyquist rate for the encoder signals. The Nyquist-rate sampling is achieved through zero-crossing detectors that turn the “sine” and “cosine” signals into digital quadrature, which can then be processed as for a digital incremental encoder into a high-frequency counter.

For high-resolution servo feedback, the counter can be latched on the servo clock simultaneously with the strobing of the A/D converters, and the “whole-count” data from the counter is then combined with the calculated “fractional-count” arctangent value from the converted analog values.

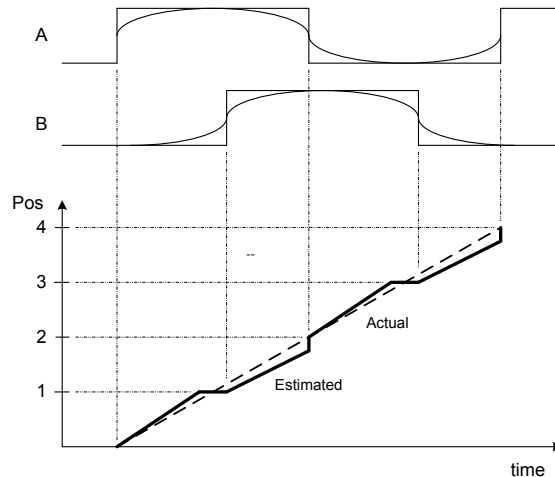


FIGURE 7. Errors in timer-based sub-count extension from unevenly spaced zero crossings

UPDATING CAPTURE/COMPARE POSITIONS

While minimizing the time elapsed in relating an I/O event to a position value can be critically important, another issue vital in many applications is the speed of preparing for the next event. As with the individual capture/compare event, the updating can be done in scanned software, interrupt-driven software, or in hardware. The required update rate usually determines which technique is used.

If the required update frequency is a few kHz or below, scanned software is typically fast enough to manage the task, storing the most recent captured position or loading the next compare position. If the frequency gets into the tens of kHz, an interrupt service routine may be required. This would have to be of higher priority than servo interrupt tasks, so great care must be taken not to interfere with servo performance.

At even higher rates, hardware techniques must be employed. One important technique is the “auto-increment” for compare outputs. If the spacing between consecutive outputs is even, this is relatively simple to implement in hardware; when a compare event occurs, the increment value is automatically added to the compare position to create the next position.

A typical implementation uses two active compare values, each of which can toggle the digital output, and a common increment value. When one compare position is reached by the active count value (possibly with fractional count extension), the other value is automatically

incremented. This “hand-over-hand” incrementing can continue indefinitely.

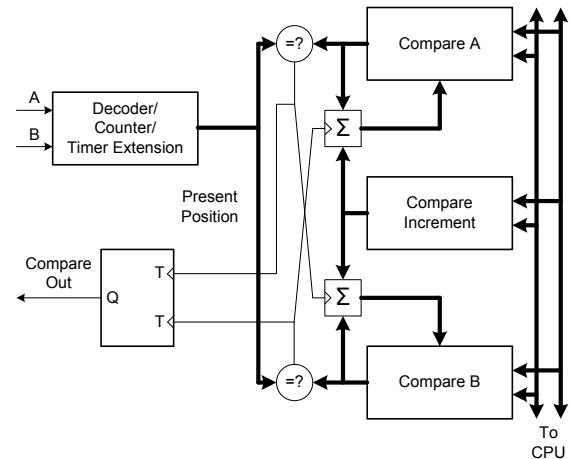


FIGURE 8. Automatically incrementing position-compare circuitry

FUTURE TRENDS

A/D converters with both very high-frequency and high-resolution capabilities have recently become available at reasonable cost. Combined with the increased performance and cost-effectiveness of programmable digital logic, the full hardware conversion of sinusoidal encoders at multiple megahertz frequency is becoming a practical reality.

In addition to permitting oversampling averaging for noise mitigation, this capability can provide for automatic detection of, and correction for, offset, magnitude, and phase errors, eliminating the largest source of errors in present position capture and compare accuracy for these sensors.

CONCLUSIONS

The advent and steady improvement of hardware-based position-capture and position-compare circuits has provided much tighter coupling between I/O events and positions, especially during motion. It has permitted many tasks to occur during motion that formerly had to be done at rest. It has also permitted much higher speeds of operation in many applications while maintaining the required level of synchronization.

ENGINEERING INTERPRETATION OF EIGENVECTOR SENSITIVITIES USING NORMALIZATION

E.C. Hooijkamp¹, H.J. Peters¹, F. van Keulen¹, J. van Eijk^{1,2}

¹Precision and Microsystems Engineering

Delft University of Technology

Delft, the Netherlands

²MICE BV

Eindhoven, the Netherlands

INTRODUCTION

Design sensitivities are used in various engineering methods to arrive at optimal or advanced designs. The design sensitivity of a system, also known as the derivative to a design variable, represents the change of the system response due to an adjustment of a design variable. Scientists and engineers often use modal design sensitivities to predict the change of a transient response. These sensitivities are the derivatives of the eigenvalues and eigenvectors of the system.

Many researchers have successfully computed modal sensitivities using several methods. Nelson's method [1] is widely used even though computationally expensive. Fox's method [2] uses a modal superposition to represent the eigenvector sensitivities by the system eigenvectors, but is inaccurate when using only a few eigenvectors. Hence, several iterative methods were proposed to increase the accuracy of Fox's method (e.g., [3] or [4]).

The primary focus of the previous research was on the computational algorithms rather than the interpretation of the eigenvector sensitivities. This interpretation depends highly on the chosen normalization. An approach for incorporating these normalizations was presented by Smith [5]. This paper shows the consequence and potential use for interpretation of the chosen normalization. This is illustrated on an example using a generic two-degrees-of-freedom system, as shown in FIGURE 2.

NORMALIZATION

The eigenvalues and associated eigenvectors of a system result from the governing eigenproblem. The eigenvectors are determined as shapes for which the amplitude is subjected to the normalization condition. This is chosen by the user or algorithm and can be altered without losing essential information. The response q of the system is expressed as a su-

perposition of the eigenvectors and eigenvalues:

$$q = \sum_k A_k v_k e^{-\lambda_k t} \quad (1)$$

where v_k is the eigenvector, λ_k is the eigenvalue, t is time and A_k is the modal amplitude. The modal amplitude is determined by the initial conditions and the load. Although the response is independent of the normalization condition, the amplitude of eigenvector is. Therefore, the modal amplitude depends on the normalization condition.

The eigenvalue and eigenvector sensitivities are determined using the derivatives of the eigenproblem to the design variables. While the eigenvalue sensitivities are extracted by pre multiplication of the transpose of the eigenvector, the eigenvector sensitivities are more tricky. To regularize the set of equations, the change of the amplitudes has to be taken into account. This change is given by the derivative of the normalization condition. One of the methods to compute the eigenvector sensitivities is Fox's method [2] defining the sensitivity as a superposition of the system eigenvectors:

$$\frac{\partial v_k}{\partial s_i} = a_{k k i} v_k + \sum_{l \neq k} a_{k l i} v_l \quad (2)$$

where v_k is the eigenvector for which the sensitivity is computed, s_i is the design variable and $a_{k l i}$ is

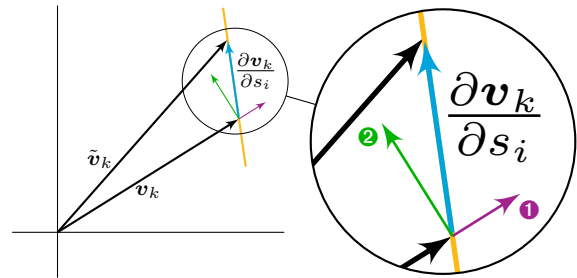


FIGURE 1. A graphical representation of an eigenvector v_k , the changed eigenvector $\tilde{v}_k$ and its sensitivity. Where vector (1) and (2) are the amplitude and shape change respectively.

the contribution of eigenvector v_l to the sensitivity.

Although the eigenvector is only a shape, the eigenvector sensitivities include both a change of the shape and the amplitude. The first term of Equation 2 represents the amplitude change and the second term represents the shape change. A graphical representation is shown in FIGURE 1. The amount of amplitude change depends on the chosen normalization. In fact the amplitude of the shape change, the second term of Equation 2, depends on the normalization as well. However, this dependency does not have to be a drawback since a specific normalization condition can add information to the eigenvector sensitivity.

Modal sensitivities can be used to predict the change of the system transient response. The sensitivity of the response is the derivative of Equation 1 with respect to a design variable. Substitution of Equation 2 into this sensitivity results in:

$$\frac{\partial q}{\partial s_i} = \sum_k \left(\frac{\partial A_k}{\partial s_i} v_k + A_k a_{kki} v_k + A_k \sum_{l \neq k} a_{kli} v_l - \frac{\partial \lambda_k}{\partial s_i} t A_k v_k \right) e^{-\lambda_k t} \quad (3)$$

The change of the response is divided into four terms containing to the change of modal amplitude, the amplitude change of the eigenvector, the shape change of the eigenvector and the change of the eigenvalue respectively. As the change of the response is independent of the normalization condition, all terms of Equation 3 are dependent. Thus, knowledge about the normalization condition is essential for the prediction of the change of the total response.

EXAMPLE

The example presented in this paper is a generic two-degrees-of-freedom system, as shown in FIGURE 2. This model can correspond to different physical fields, such as thermal, dynamics or statics. FIGURE 3 and 4 show the two eigenvectors of the system and their sensitivities to the design variables s_1 , s_2 and s_3 (see FIGURE 2). FIGURE 3 shows the eigenvectors normalized for its magnitude equal to one. For this normalization, the eigenvector sensitivities do not include an amplitude change as the magnitude is constraint. FIGURE 4 shows the same eigenvectors, but in this case, normalized such that the amplitude is equal to its modal response to a constant load on the left degree of freedom. In this

normalization, the eigenvector sensitivities include an amplitude change containing information about the change of the response.

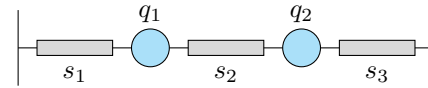


FIGURE 2. Model of a generic two-degrees-of-freedom system (e.g., dynamics or thermal model), where q_i and s_i are the state and design variables respectively.

First consider a case where the goal is to understand the effect on a specific eigenvector, for instance a buckling analysis. In this case, the interpretation using the normalization with respect to the magnitude of the eigenvector is preferred, because the sensitivity consists only of the change of the shape of the eigenvector ($a_{kki} = 0$). From Equation 2 it is seen that the eigenvector sensitivity is constructed by the other eigenvectors. For this two-degrees-of-freedom system the change of the first eigenvector is constructed using only the second eigenvector and the other way around, as seen in FIGURE 3.

Next consider a case where the goal is to understand the effect on the total response of the system when the load is known. For instance a temperature or displacement field of a system with recurrent loads. In that case, the interpretation using the normalization with respect to the magnitude of the eigenvector is not preferred. The change of the shape of the eigenvector gives a limited inside in the change of the response, as shown in Equation 3. The interpretation using the normalization with respect to the modal amplitude of the system is therefore preferred in this case. The eigenvectors are then normalized such that the amplitude is equal to its modal response to a constant load on the left degree of freedom. The response q yields

$$q = \sum_k \tilde{v}_k e^{-\lambda_k t}$$

and Equation 3 becomes:

$$\frac{\partial q}{\partial s_i} = \sum_k \left(a_{kki} \tilde{v}_k + \sum_{l \neq k} a_{kli} \tilde{v}_l - \frac{\partial \lambda_k}{\partial s_i} t \tilde{v}_k \right) e^{-\lambda_k t}$$

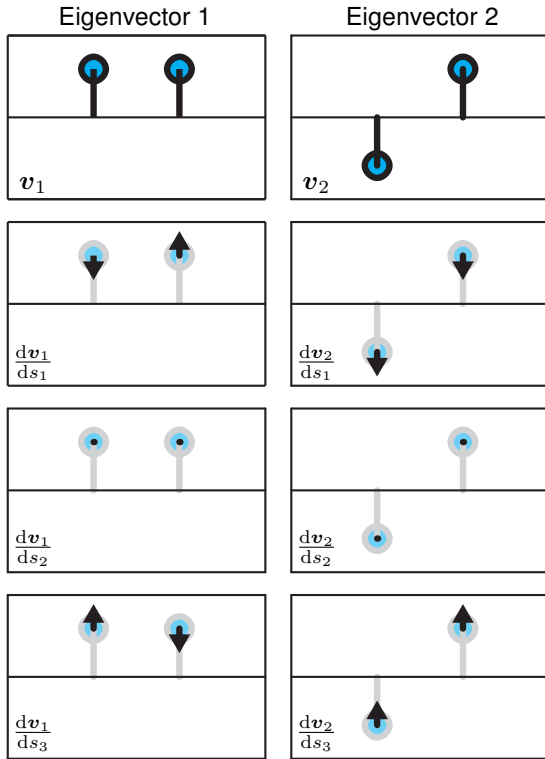


FIGURE 3. Eigenvectors and its sensitivities normalized with respect to its magnitudes.

Both normalization conditions can aid the interpretation of the eigenvector sensitivities for a given problem. Hence, the normalization condition should depend on the problem for a better engineering interpretation.

CONCLUSION

Although several methods exist to compute eigenvector sensitivities, the normalization condition affects the shape and amplitude of the sensitivities. However, this normalization can add information and so aid the interpretation. Thus, it depends on the problem and engineering method which normalization condition one should use to normalize the eigenvectors and its sensitivities.

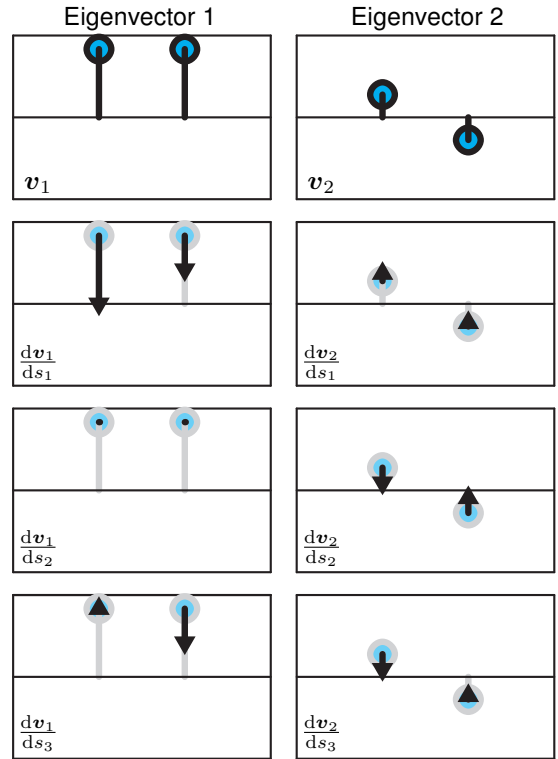


FIGURE 4. Eigenvectors and its sensitivities normalized such that the amplitude is equal to its modal response to a constant load on the left degree of freedom.

REFERENCES

- [1] Nelson R. Simplified Calculation of Eigenvector Derivatives. *AIAA Journal*. 1976;14(9):1201–1205.
- [2] Fox R, Kapoor M. Rates of change of eigenvalues and eigenvectors. *AIAA Journal*. 1968;6(12):2426–2429.
- [3] Alvin K. Efficient Computation of Eigenvector Sensitivities for Structural Dynamics. *AIAA Journal*. 1997;35(11):1760–1766.
- [4] Bobillot A, Balmès E. Iterative Computation of Modal Sensitivities. *AIAA Journal*. 2006;44(6):1332–1338.
- [5] Smith D, Siddhi V. Generalized Approach for Incorporating Normalization Conditions in Design Sensitivity Analysis of Eigenvectors. *AIAA Journal*. 2006;44(11):2552–2561.

ROBUSTNESS ANALYSIS OF DYNAMICS AND CONTROL A NEW METHOD TO SUPPORT HIGH PERFORMANCE OPTICAL MANIPULATOR DESIGN

Ulrich Schönhoff
Mechatronic Design Department (Lit-TM)
Carl Zeiss SMT GmbH
Oberkochen, Germany

ABSTRACT

The performance of an optical manipulator is often limited by the structural dynamics of its components. Moreover, the structural dynamics is subject to tolerances, parameter variations, and modelling errors, further limiting the achievable performance of the manipulator. In order to account for these uncertainties, this paper proposes the application of a robustness analysis in the process of the manipulator design. This approach optimises the manipulators mechanical design for maximum performance and ensures its achievement in practice.

INTRODUCTION

Lithography optics has taken the step from lenses for DUV to mirrors for EUV. This step puts high demands on the position stability of the actively manipulated mirrors. Compared to lens-based systems, mirror-based systems have a significantly higher sensitivity of image stability to mirror motion. In terms of mechatronics, this translates into tough requirements on the control bandwidth for the position control loop of the actively controlled optical manipulators.

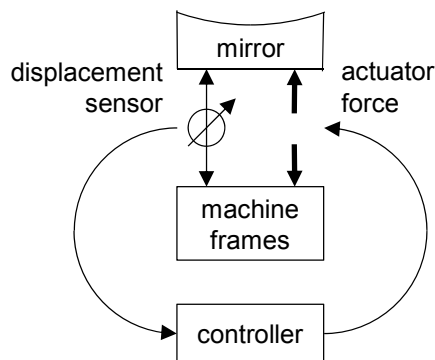


FIGURE 1: Scheme of an optical manipulator.

The task of the mirror manipulator is to keep the mirror stable at a certain position in up to all 6 of the mirrors degrees of freedom (DoF) and to vary the position set point within a certain range. The mechatronic components of the manipulators are a set of displacement sensors, a set of actuators and a multivariable position controller. In addition, the optical manipulator contains different frames providing a position reference for the sensors and for absorbing the actuator forces (figure 1).

The basic PID control concept of such manipulators considers the mirror as a rigid body and allows theoretically unlimited bandwidth of the mirror's position control loop. However, for a real manipulator the bandwidth is limited by the undesired but inevitable flexible eigen modes of the mirror and of the involved components such as actuators and frames. This limitation cannot be overcome by controller tuning, if the natural frequencies reside in a rather broad frequency range around the desired bandwidth.

Therefore, the focus lies on designing the plant rather than the controller. This means designing the structural dynamics of the mirror and its surrounding components. This is done by repeated modelling and analysis of the control loop and by subsequent improvement of the shape and topology of the mechanical components.

It is state of the art to model the structural dynamics of the components by FEM and to integrate these FE-models into the dynamic model of the control loop. This allows to analyse the impact of the components structural dynamics on the control loop and to motivate design modifications of the components [1, 2].

However, FEM models do not exactly match reality. Further, the structural dynamics can be sensitive to tolerances and/or parameter

variations of critical components. To achieve the designed performance in practice while pushing the performance to its limit, these uncertainties need to be considered in the design.

ROBUSTNESS ANALYSIS

FE-models reflect the dynamical response of the mechanical system for the designed parameters. The real dynamics might deviate from it for the following reasons:

- Tolerances of the mechanical parts
- Expected parameter variations
- Uncertainties of the modelling

The tolerances of mechanical parts are unavoidable. For dynamically sensitive parts such as monolithic hinges, they can have a significant impact on the system dynamics. The same is valid for expected parameter variations, for instance variations of the payload of a machine or macroscopic moves of machine parts such as stages or portals. Uncertainties in the FE-modelling, like modelling of contacts and connection also lead to errors in the resulting dynamics of the model.

For a robust and optimal design these uncertainties need to be considered in the analysis and design process.

Uncertainty Modelling using LFTs

Ad hoc, modelling of parameter variations would mean to repeatedly built FE-models with changed parameters. The course of action from CAD via FE-modelling to a modal state-space representation is very labour-intensive. To reduce the workload the concept of Linear Fractional Transforms (LFT) is applied. It allows to use a single model for robustness analysis [3]. The parameters are varied by feeding back additional outputs to additional inputs. Figure 2 shows the general block diagram of an LFT.

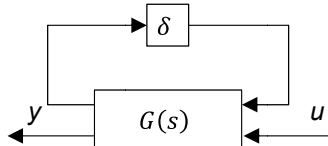


FIGURE 2: Linear Fractional Transform (LFT)

A simple example is the SISO static gain of the form $y = (\alpha + \beta\delta)u$. The nominal static gain α is supposed to be varied by a uncertainty variable δ . As a convention δ is normalised to $\delta \in [-1, 1]$. The variation is scaled by β . This is realised by choosing

$$G(s) = \begin{bmatrix} \beta & 0 \\ 1 & \alpha \end{bmatrix}.$$

Closing the LFT feedback loop with the uncertainty δ yields the desired gain perturbation $y = (\alpha + \beta\delta)u$.

The concept of LFTs further allows to first define uncertainties on sub-system level and to connect the uncertain sub-systems subsequently to a single state-space representation of the full model.

Uncertainty Modelling for Mechanical Systems

Uncertainty of lumped Parameters

Often, modelling of critical tolerances and parameter variations can be boiled down to uncertainties of lumped springs, dampers and/or masses. These uncertain elements can be added effectively to a nominal FE-model.

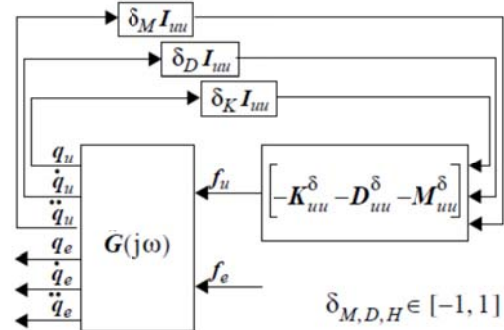


FIGURE 3: LFT-modelling of uncertainty of lumped mechanical parameters [5].

First, the DoFs of the nodes, where the lumped elements are attached, need to be exported additionally from the FE-model. When building up the state-space representation these DoFs need to be assigned as additional inputs and outputs. Depending on the type of parameter - spring, damper or mass - displacements, velocities or acceleration need to be used as outputs q_u , $\dot{q}_u$ or $\ddot{q}_u$ whereas all inputs are forces f_u acting on the specific DoFs. Next, the element matrices K_{uu}^δ , D_{uu}^δ or M_{uu}^δ of the lumped spring, damper or mass variation need to be derived. Finally, a LFT is constructed by feeding back the displacements, velocities or accelerations q_u , $\dot{q}_u$ or $\ddot{q}_u$ via the element matrices K_{uu}^δ , D_{uu}^δ or M_{uu}^δ and the normalized uncertainty variables δ_K , δ_D or δ_M to the input force f_u (figure 3).

Uncertainty in natural Frequencies

FE-modelling of flexible structures is typically quite precise in the shapes of fundamental modes. Though, the belonging natural

frequencies can have a considerable error. Furthermore, even small uncertainties of natural frequencies can have a significant impact on the FRF at a particular frequency of interest due to the sharpness of the resonances of lightly damped structures.

For the integration in an model of the control loop, FE-models are typically transferred into a modal state-space representation [1, 5, 6]. Such a state-space representation shows a block-diagonal structure

$$\dot{x} = \begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_N \end{bmatrix} x + \begin{bmatrix} B_1 \\ \vdots \\ B_N \end{bmatrix} u$$

$$y = [C_1 \quad \dots \quad C_N]x + Du$$

with a 2×2 matrix A_i

$$A_i = \begin{bmatrix} 0 & 1 \\ -\omega_{0i}^2 & -2\xi_i\omega_{0i} \end{bmatrix}$$

per mode.

We introduce a scaled uncertainty $\beta_i\delta_i$ in the natural frequency ω_{0i} of the mode i with $\delta_i \in [-1, 1]$ and β_i a scalar, such that

$$A_i = \begin{bmatrix} 0 & 1 \\ -(\omega_{0i}(1 + \beta_i\delta_i))^2 & -2\xi_i\omega_{0i}(1 + \beta_i\delta_i) \end{bmatrix}.$$

The modal damping ξ_i is kept constant.

Since ω_{0i} appears twice in A_i , once quadratic and once linear, this would require two scalar uncertainty variables per mode in the LFT representation [4]. In order simplify the anyhow computationally intensive robustness analysis, the number of LFT outputs and inputs is reduced here from two to one. This is done by linearising the term

$$(\omega_{0i}(1 + \beta_i\delta_i))^2$$

to

$$\omega_{0i}^2 + 2\omega_{0i}^2\beta_i\delta_i,$$

which is valid for small uncertainties. A_i can be rewritten as

$$A_i = \begin{bmatrix} 0 & 1 \\ -\omega_{0i}^2 & -2\xi_i\omega_{0i} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \delta_i [-2\omega_{0i}^2 \quad -2\xi_i\omega_{0i}]$$

and the uncertainty can be represented in a LFT

$$\dot{x} = A_i x + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} u_{\delta_i} \\ u \end{bmatrix}$$

$$\begin{bmatrix} y_{\delta_i} \\ y \end{bmatrix} = \begin{bmatrix} -2\omega_{0i}^2 & -2\xi_i\omega_{0i} \\ C_i \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 0 & D \end{bmatrix} u$$

with the single scalar uncertainty variable δ_i per mode [5, 6].

Robustness Analysis

The development of a model with a LFT representation of the uncertainty opens the door to robustness analysis. There are several approaches to perform the robustness analysis.

The brute-force approach is a grid search. For each uncertainty variable a grid over its

range is defined. The system is analysed by permuting all combinations of the gridded uncertainty values. This approach gives great freedom in choosing the aspects of the analysis. One can analyse the pole locations and with this stability. Further, FRFs and even time responses of the perturbed system can be computed. Finally, a statistical analysis of the properties of the perturbed system is possible. This approach is efficient, if the number of uncertainty variables is small. For large numbers of variables excessive computation time can be required to compute all combinations. The grid search is used in the two following examples.

To analyse systems with a larger number of uncertainties, μ -analysis [3] is one of the most established algorithms. Efficient solvers are available [7]. μ -analysis allows to consider a broad variety of types of uncertainty variables, such as complex, real, repeated scalar and matrix-valued variables. It does not require to grid the variables. Though, the analysis is restricted to the worst-case in frequency domain. It can analyse the robustness of stability and whether a certain number FRFs of interest lie robustly below a certain bound. A possible exceedance can neither be precisely quantified nor be assigned to a particular FRF without further analysis.

The typical view of robustness analysis is the analysis of closed-loop stability and performance. However, for the system design it is of special interest to quantify a potential robustness problem in an open-loop view in order to be able to derive solutions. This illustrated in example 2.

EXAMPLE 1: ACTUATOR RESONANCES

The first example is the investigation of a uncertain actuator stiffness on the stability and performance on the controlled optical device. In this example the actuator masses of the actuators are mounted with a limited stiffness to a mirror as depicted in figure 4. This results in resonances, which are visible and relevant in the position control loop. The controller is designed for the nominal model such that these resonances are stabilised and damped properly. Regarding the practical realisation, the question arises, whether the control loop will show robust stability and performance in the presence of stiffness tolerances.

For this purpose the FE-model of the optical mechanism has been extended by a LFT representing the uncertainties of the lumped stiffnesses with a scalar uncertainty variable per

actuator. The complete model of the control loops is composed from the FE-model of the mechanism, linear models for sensors and actuator and the controllers.

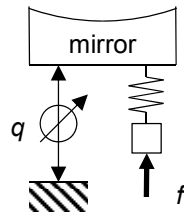


FIGURE 4: 1-DoF scheme of an optical manipulator with actuator resonances.

The analysis is carried out in closed loop configuration using the grid search approach. The robustness of the stability is analysed by viewing the closed-loop pole locations. As shown in figure 5 this example is robustly stable, i.e. stable for all variations. Though, the poles corresponding to the actuator modes tend towards the imaginary axis.

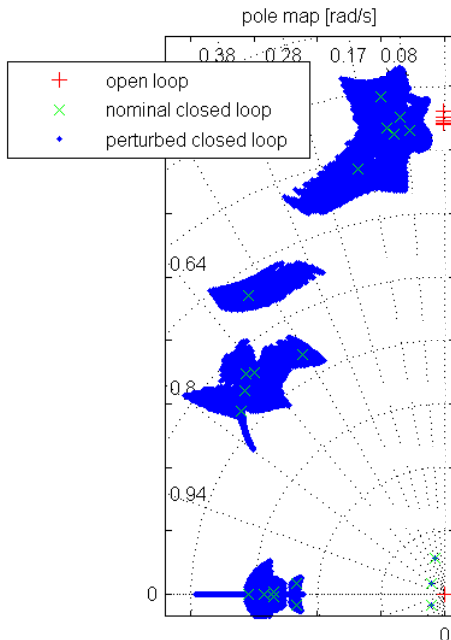


FIGURE 5: Pole map.

The performance is measured in terms of the control loop's sensitivity function. Figure 6 shows the sensitivity function of the nominal model and the envelope of all variations investigated. For this example there is a significant decrease of the performance visible in the frequency range of the actuator resonances.

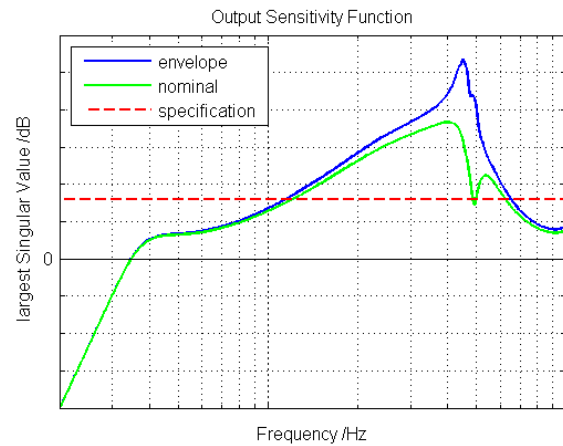


FIGURE 6: Envelope of the sensitivity function.

EXAMPLE 2: MULTIPLE FRAME RESONANCE EFFECT

The second example treats an issue we refer to as the “multiple-frame-resonance effect”. The set-up depicted in figure 7, shows an optical manipulator which is supported by two frames. Frame 1 has the function to absorb the reaction forces of the actuator. Frame 2 carries the position sensors and is dynamically decoupled from frame 1 by weakly suspending springs.

This decoupling works perfect for theoretic rigid frames. In reality frames are flexible. This leads to the risk of significant degradation of the decoupling. In case of coinciding natural frequencies of flexible modes of the two frames, the resonance peak of one frame is amplified by the resonance peak of the other frame. Because of the typically weak damping of the flexible modes, the amplification can reach large factors. We denote this the multiple-frame-resonance effect.

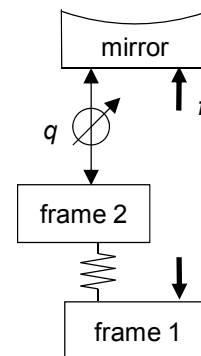


FIGURE 7: Analysed set-up of example 2.

The multiple-frame-resonance effect is very sensitive to uncertainties in modelling of the frame dynamics. Thus, it cannot be modelled

reasonably by a single model. Therefore, a robustness analysis considering uncertainties in the natural frequencies of the frames is required.

In order to quantify the potentially lacking amount of decoupling, the analysis is performed open loop. Further, the open loop $GC = (G_A + G_R)C$ is decomposed in an action path open loop $G_A C$ and a reaction path open loop $G_R C$ in order to view the frame dynamics independently from the mirror dynamics. The reaction path is the transfer function from the actuators reaction forces applied to frame 1 to the sensor displacements of frame 2 (figure 7, 8). The closed loop output sensitivity function $S_o = (I + (G_A + G_R)C)^{-1}$ can be written as $S_o = (S_{oA}^{-1} + G_R C)^{-1}$, with the output sensitivity function $S_{oA} = (I + G_A C)^{-1}$ for an ideal, non-existing reaction path. The admitted peak of the sensitivity function S_{max} is

$S_{max}^{-1} = \|S_{oA}^{-1} + G_R C\|_{\infty} \leq \|S_{oA}^{-1}\|_{\infty} - \|G_R C\|_{\infty}$.
It leads to

$$\|G_R C\|_{\infty} \leq \|S_{oA}^{-1}\|_{\infty} - \frac{1}{S_{max}}$$

as a condition for action path open loop gain $G_R C$ for not hampering the action path's performance. Typically $\|G_R C\|_{\infty} \ll 1$.

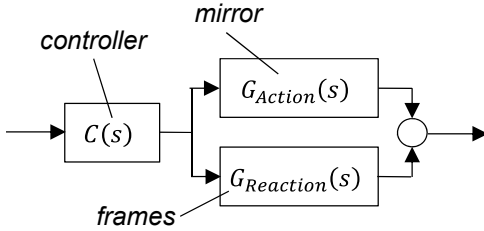


FIGURE 8: Separation of action and reaction path.

To model the reaction path, at first separate FE-models of the two frames are set-up. Subsequently, the models are augmented with LFT representations of uncertainty in natural frequency for each flexible mode of corresponding frame. By treating the suspension springs as input/output systems mapping relative position to a force we couple the two frames by feedback interconnection according to figure 9. The error occurring from interconnecting individually reduced models in this way is insignificant for weak springs. It leads to a single integrated state-space model of the two frames, which still allows to vary each natural frequency of the two frames individually and independently.

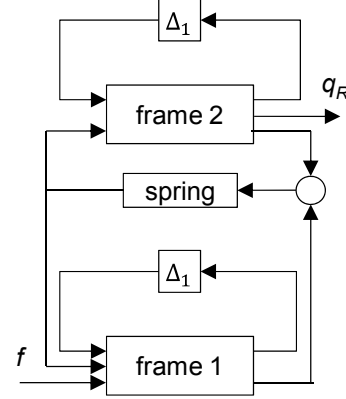


FIGURE 9: Block diagram of the reaction-path model.

The analysis is carried out by a grid search, i.e. varying the natural frequencies of the frames on a fine grid in a defined range via the LFTs and calculating the frequency response function (FRF) of the open loop reaction path repeatedly. For simplification all natural frequencies of one frame are varied equally by a single scalar uncertainty variable. Further, the natural frequencies of frame 1 are kept fixed, while the natural frequencies of frame 2 are varied relatively to those of the frame 1.

The results of this example are viewed from three perspectives: The envelope FRF of the reaction path open-loop of all perturbed models gives the information of worst-case peaks vs. frequency. For this example the reaction path open-loop FRF exceeds even gain 0 dB at multiple frequencies and is significantly above the prediction of the nominal model. Thus, the reaction path design needs significant further decoupling. The required amount can be read from the graph.

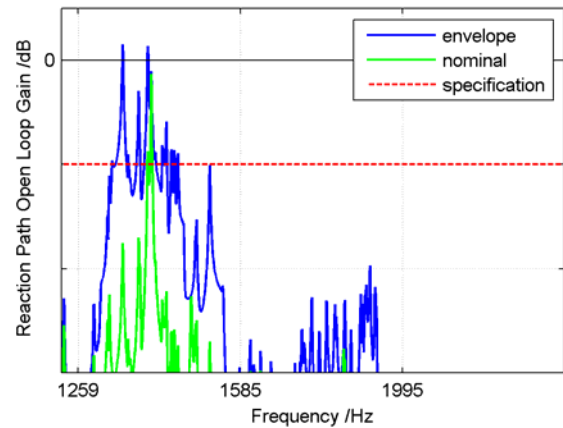


FIGURE 10: Open-loop reaction path envelope FRF.

The second perspective is the maximum peak of the open-loop reaction path FRF vs. the variation of the natural frequencies of frame 2 relative to frame 1. This representation shows which particular parameter variation causes large peaks in the FRF. It nicely illustrates the multi-frame-resonance effect. If resonances of the two frames are tuned such that their natural frequencies coincide, the reaction path shows a large peak.

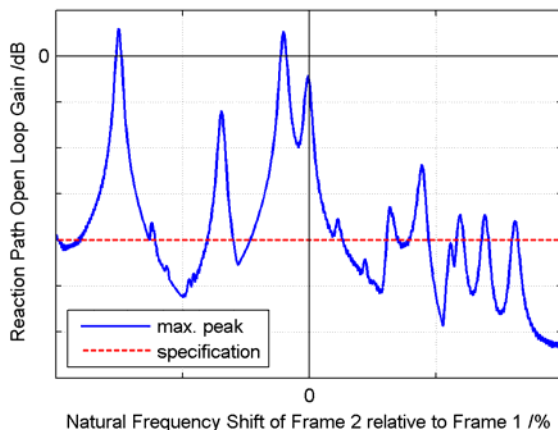


FIGURE 11: Open-loop reaction path peaking vs. natural frequency variation.

The probability function of the maximum peak of the reaction path open loop FRF (for a certain considered probability distribution of the frame's natural frequency uncertainty) shows the probability for the FRF to exceed a certain defined level. Beyond the worst-case view, this allows a statistical quantification of the required additional decoupling. In this example, the designed manipulator will meet its specification in reality with a probability of about 40%

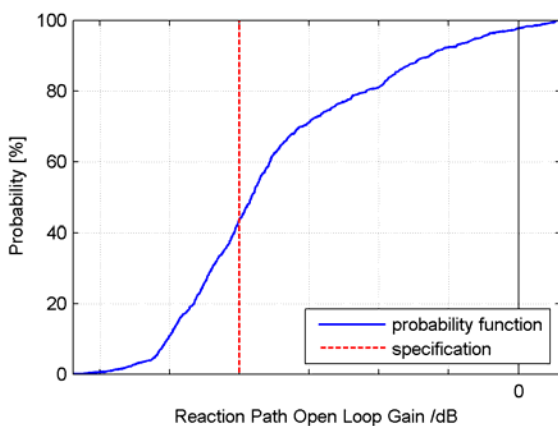


FIGURE 12: Probability function of the Open-loop reaction path peaking.

CONCLUSIONS

The representation of uncertainties in terms of Linear Fractional Transforms allows to conduct robustness analysis based on a single FE-model. The approach of grid search offers large flexibility in the aspect of analysis, especially probability. Though, it becomes computationally expensive for many uncertainty variables. Open-loop analysis of the reaction path gives a straight-forward quantification of the required amount of improvement to be archived in the next loop of component optimisation. Above all, the proposed step of robustness analysis in the design process of an optical manipulator allows to identify and quantify the sensitivity of a design to uncertainties in the structural dynamics. Thereby, it serves to optimise the components design.

ACKNOWLEDGEMENTS

Thanks to Rob de Jongh and Marc von der Wijst of ASML and to my colleagues Eylem Bektas, Bernhard Geuppert and Stefan Haarhoff of Carl Zeiss SMT GmbH for their valuable advice and fruitful discussion.

REFERENCES

- [1] Rankers, A.M.(1997): *Machine Dynamics in Mechatronic Systems. An Engineering Approach*. PhD Thesis, Delft University of Technology.
- [2] Schönhoff, U.; Eisenträger, P.; Wandner, K.; Kärcher, H.; Nordmann, R. (2000): End-to-end Simulation of the Image Stability for the Airborne Telescope SOFIA. *Proceedings of SPIE* **4014**, 380-391.
- [3] Skogestad, S.; Postlethwaite, I. (2006): *Multivariable Feedback Control. Analysis and Design*. 2nd edition. Wiley.
- [4] Smith, R.. (1995): Eigenvalue perturbation models for robust control. *IEEE Tans. on automatic control* **40**(6) 1063-1066.
- [5] Schönhoff, U., Eisenträger, P.; Nordmann, R. (2000): Reduction of finite element models of flexible structures for controller design and integrated modeling. *Int. Conf. on Noise and Vibration Engineering, ISMA25*, Leuven, Belgium.
- [6] Schönhoff, U. (2003): *Practical Robust Control of Mechatronic Systems with Structural Flexibilities*. PhD Thesis, Darmstadt University of Technology, *Forschungsberichte Mechatronik & Maschinenakustik*, Shaker Verlag, Aachen.
- [7] Matlab Robust Control Toolbox. <http://www.mathworks.com/products/robust/>

PARALLEL KINEMATICS AND 6-DOF ACTIVE DAMPING IN HIGH ACCURACY VACUUM APPLICATIONS

Gloess, Rainer¹; Oberfell, Joachim²; Mock, Christopher¹;

¹ Physik Instrumente (PI) GmbH & Co. KG, Auf der Roemerstr. 1,
76228 Karlsruhe, Germany

² PI miCos GmbH, Freiburger Str. 30, 79427 Eschbach, Germany

INTRODUCTION

The paper describes different parallel kinematics structures for 6D precision positioning applications in medium and ultrahigh vacuum. Inspection tools in the semiconductor industry, laser alignment and adjustment tools for the next generation of EUVL require extremely precise motion in all 6 degrees of freedom. This can be achieved with high flexibility using hexapod and tripod systems.

Three special systems for 6-DOF motion are discussed. Each of them is UHV compatible and can be freely configured. The paper will also discuss a 6-DOF active vibration damping structure integrated into a constant-strut-length hexapod with its active drives placed outside the vacuum chamber.

HEXAPOD AND TRIPOD CONFIGURATIONS

- Steward Platform with piezo actuators
- SpaceFab
- Constant-strut-length design for vacuum

6-DOF INSPECTION SYSTEM

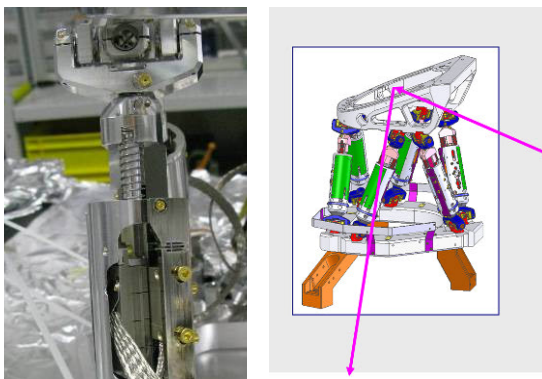


Figure 1: Ultra-high vacuum hexapod inspection tool

An inspection tool for qualifying reflective optics was designed based on a hexapod system. The hexapod platform is placed inside the vacuum chamber and carries the freeform-shaped test mirror.

Actuators:

The struts are driven by NEXACT® piezo linear motors. NEXACT® technology is well proven for high-vacuum applications. Four 4-finger actuator, double-modules are combined in one drive section. On order to prevent any unwanted deformation the actuators are placed in a pre-loaded flexure-guided frame.

Sensors:

Position feedback is based on high-resolution Heidenhain optical incremental sensors. The LIA21 and LIP481U series of encoders is designed for high vacuum applications. One drawback is the relatively high power dissipation caused by the sensor LED and the sensor electronics. This would lead to an expansion of the sensor flange and the surroundings. Therefore we placed the sensors on Invar flanges as a reference while increasing the distance to the surrounding material as much as possible. The design of such a hexapod actuator is shown in figure 2.

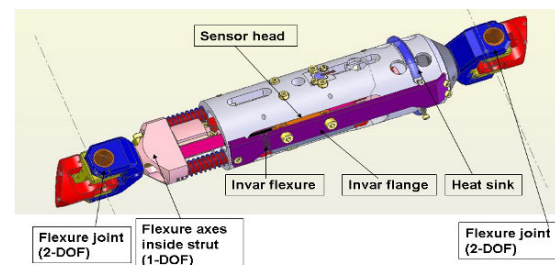


Figure 2: Hexapod actuator with incremental sensor and heat sink

'SPACE FAB' TRIPOD SYSTEM FOR 6 DOF

The PI miCos tripod system is a 6-DOF manipulator consisting of three X-Y stages (with 6 actuators) and three passive struts. The advantage of such a setup is the large and well-defined rectangular motion range in both the X and Y direction. It can be designed with a low profile height to fit into small vacuum chambers. The system can be easily reconfigured with different linear motion axes (X-Y stages) and the number of three times 2-DOF joints is small compared to other 6-DOF systems..



Figure 3: SpaceFab configuration for long travel ranges in XY

Such systems are placed in semiconductor inspection tools. Stepper motors are employed for high vacuum applications with and without high precision linear encoders for servo loop operation. The three joints consist of sapphire and hybrid bearings are used in the three rotation axes on the struts.

- Sapphire
- Hybrid bearing (ceramics and stainless steel)
- Crimping of wires if possible
- Stepper motors

CONSTANT STRUT-LENGTH HEXAPOD

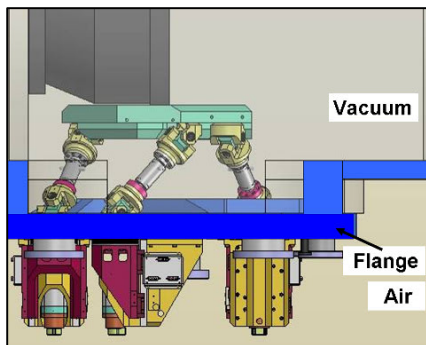


Figure 4: Hexapod structure with linear guided joints and active vibration damping system

For high vacuum applications and high plasma stream influence it is advantageous to shift all active parts and electronics out of the vacuum. This is feasible using 6-DOF hexapod systems with passive struts and linear guided joints mounted perpendicularly to the flange of the vacuum chamber. Because of the pure linear motion of the joints metal-bellows can be used to seal the vacuum.

ACTIVE DAMPING IN 6 DOF

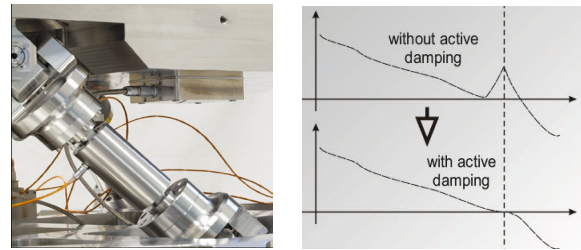


Figure 5: Piezo actuators integrated in hexapod strut

The constant-strut-length hexapod design can also easily be modified to incorporate additional active damping inside the vacuum chamber. Pre-loaded piezo actuators are placed inside the six struts and a newly developed 6-D vacuum-sealed acceleration sensor was placed at the platform.

Using PI's digital modular controller for the 6-DOF transformations, damping factors in excess of -20dB for multi-directional vibrations were achieved.

CONCLUSION

Parallel kinematics positioning systems are available for high vacuum and high accuracy applications. Use of vacuum compatible material, drives and sensors was discussed. With linear guided hexapod systems the implementation of 6-DOF vibration damping inside the vacuum is feasible.

REFERENCES

- [1] Hexapod Systems for UHV Applications with Active Vibration Damping: C. Rudolf, C. Mock, R. Gloess, Proc. EUSPEN 2011
- [2] Positionieren im Vakuum: W. Meienburg, Photonics, 3/2006, pp.58-59

Optomechanical characterization of large wafer stepper-optics with respect to centering errors, lens distances and center thicknesses

Daniel Stickler, Bernd Lürß, Patrik Langehanenberg, Josef Heinisch,
and Eugen Dumitrescu
TRIOPTICS GmbH
Wedel (Hamburg), Germany

One key technology in mass microchip-production is an optical projection system (wafer stepper) for deep UV photolithography. Modern wafer stepper-optics featuring sub-200nm resolution, consist of 20 to 25 glass elements with a weight of up to 1000 kg.

After the careful glass element-manufacturing, the optical performance of the system is highly influenced by the precise mechanical alignment of all individual lens elements. The imaging quality of such systems is extremely sensitive to centering errors as they may severely degrade the imaging quality. Therefore, the optical design of a stepper optic is tightly tolerated for the alignment in the sub- μm and arc second range.



FIGURE 1: Measurement instrument for the optomechanical characterization of large optical systems, e.g. stepper objective-lenses with control cabinet and PC.

Measurement instruments for real time observation during assembling and final characterization with a high resolution are rare for these types of massive optics and ultimate engineering requirements. Techniques like interferometry are able to determine the wave front, but the meas-

urement gives no quantitative results for the alignment errors of all single elements.

We will present the first commercially available high-resolution optical measurement system, which is specifically designed for large optics. For the complete optomechanical characterization, the instrument combines two high resolution focusing autocollimators and a low coherence-interferometer. The autocollimators reveal the exact centering errors of the optical elements and the low coherence interferometer determines the distances between surfaces. Both methods are non-destructive, quantitative and can be applied to assembled multi-element optics [1,2]. That means geometrical positions of all single surfaces of the final optical system can be precisely analyzed. Beside the final optomechanical characterization of the complete lens assembly, the instrument is suitable for precise lens element centering during the assembly process and automated lens-to-mount alignment.

The system performs quantitative non-contact measurements of centering errors of single elements and fully assembled optics with a measurement accuracy of $0.1 \mu\text{m}$, and accurate determination of air gap-distances and lens center-thicknesses with a measurement accuracy of $1.0 \mu\text{m}$.

TABLE 1: Overview of the instrument accuracy and maximum sample properties

Centering Error Accuracy	$0.1 \mu\text{m}$
Lens thickness Accuracy	$1 \mu\text{m}$
Air gap Accuracy	$1 \mu\text{m}$
Maximum Sample Height	2 m
Maximum Sample Weight	1500 kg
Maximum Sample Diameter	800 mm

Figure 1 shows a photograph of the measurement system (instrument stand, the control cabinet and the PC table) and Table 1 gives an overview of the main instrument specifications.

The fully PC-controlled instrument consists of a granite table with a linear air-bearing granite-column. This all-granite, all-air-bearing construction provides exceptional stiffness and thermal stability. The resulting extremely smooth motion enables the unrivaled accuracy (Tab.1).

The maximum sample diameter, given by the diameter of the rotation air bearing, is 800 mm with a maximum load of 1500 kg. To load such a heavy sample onto the instrument the upper measurement head on the linear air-bearing can be pivoted away to clear the room.

Measurement of the centering errors

The measurement of the centering error is carried out with an electronic autocollimator. For every optical surface of a system under test the position of the autocollimator and a suitable focusing optic are chosen in such way that the light emerging from the autocollimator is projected almost perpendicularly onto the surface. This results when the absolute position of the focus position along the optical axis coincides with the z-position of the center of curvature of the surface. A fraction of the light will be back reflected and forms an autocollimation image of the autocollimator target (usually a cross hair) on a digital camera device, e.g., a CCD camera. If the center of curvature of a surface is decentered with respect to a given reference axis of the measurement system, the image of the cross will be shifted. This can precisely be quantified when rotating the sample by the high precision air bearing. In this case the path of the cross hair image forms a circle on the CCD camera. The center of the circle is determined and diameter of the circle is related to the centering error of the surface (see Fig. 2) [1]. The last point of the circle yields the direction of the centering error.

For the measurement of the centers of curvature of inner optical surfaces within an assembled system the principal concept stays the same. But in order to provide an almost perpendicular incidence of the measurement light coming from the autocollimator onto the surface under test, the refraction of the optics that were traveled through to reach the surface need to be considered. The axial position of the center of curvature of such surfaces can easily be calculated if the basic design parameters of all surfaces are known: the radius of curvature, refractive index and the lens thickness. Furthermore, these pa-

rameters have to be taken into account for calculating the positions of the corresponding centers of curvature [3].

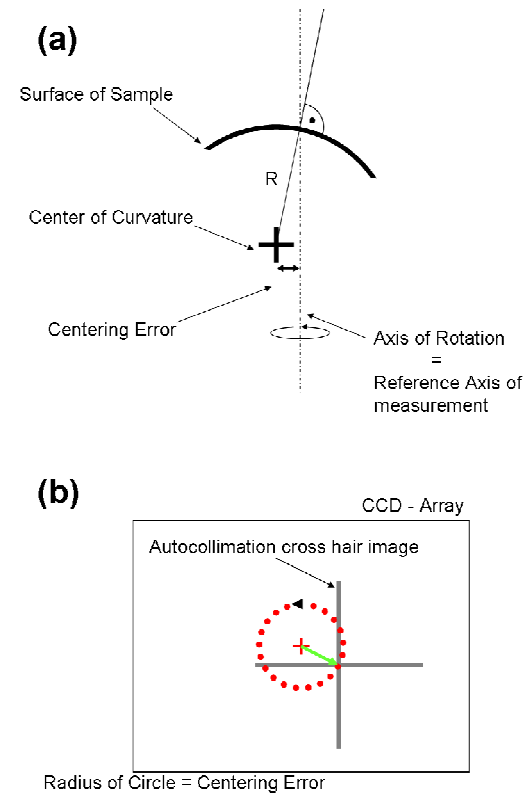


Figure 2: Measurement of the xy-position of the center of curvature with a focusing autocollimator: (a) Centering Error of the upper center of curvature to the axis of rotation, (b) circular movement of the autocollimation cross hair-image on the CCD Array.

In the measurement the surfaces are successively analyzed for the deviation of each center of curvature with respect to the reference axis. In the presented measurement system, the rotation axis of the air bearing represents the reference of each measurement. The obtained data are processed in order to provide the shift and tilt of an individual lens or group of lenses. In the analysis, the centering errors can also be transferred with respect to a different axis, e.g., the best-fit axis through all centers of curvature. Alternatively, it can be the optical axis of a single element of a defined group of lenses. In addition, the determination of the orientation of the best-fit axis itself represents a robust indicator for the alignment of the sample with respect to the reference axis.

The operator obtains a numerical and graphical output of the complete centering status regarding shift and tilt of all surfaces. The results can be transferred to a different reference system.

Measurement of air gaps and lens center thicknesses

The measurement of air gaps and lens thicknesses yields a different set of parameters for the evaluation of mechanical errors. Lens gaps and center thicknesses are defined as the geometrical distance between neighboring optical surfaces along the optical axis of an optical system. In this contribution, the positions of the optical surfaces are determined by means of low coherent interferometry.

In general, low coherent interferometry is based on the determination of the position of zero group delay difference within an interferometer system. In an interferometer, e.g., a classical Michelson-type (Fig. 3), the light coming from a low coherent light source, e.g., a spectrally broadened light source, is split by a beam splitter into an object and a reference wave. In the presented case, a superluminescent diode (SLD) at 1310 nm with a coherence length of approx. 25 μm was used. The object wave illuminates the lens system along its optical axis. In every surface, a fraction of the incoming light beam is reflected. This light is guided to a photo detector where it is superimposed with the reference light that is varied in the optical path length (OPL) by an optical delay line. When analyzing the resulting intensity as a function of the delay (Fig. 3), interference patterns are observed whenever the optical path lengths in the two interferometer arms coincide. There, the group delay difference equals zero. Thus, the location of every object surface can be determined from the positions of the maximal modulation in the interference pattern.

An important prerequisite for the detection of every single optical surface is a sufficient intensity of the back-reflected light. Besides the optimized focusing of the object beam to obtain reflections with balanced intensities from all surfaces, it is essential to align an accurate coincidence of the measurement axis of the low coherent interferometer and the optical axis of the sample. This is a critical issue for optics with spherical surfaces, and of particular importance for multi-surface samples.

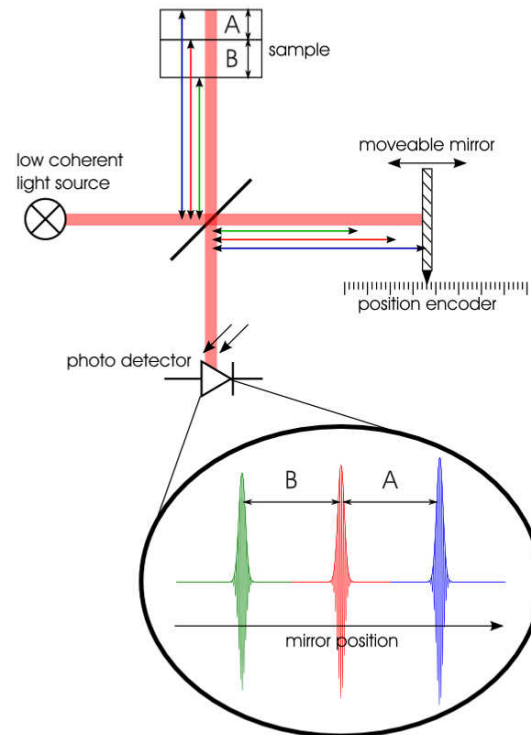


Figure 3: Measurement principle for the determination of air gaps and center thicknesses

The particular advantage of the presented measurement system is the combination of the low coherent method together with techniques for the determination of centering errors.

The centering error measurement is able to determine and align the lens group-axis of interest to the measurement axis of the interferometer. The group-axis of interest is for example the best-fit axis though all centers of curvatures, which is identical to the optical axis of the lens assembly if there is no centering error.

The measurement head of the low coherent interferometer is part of the dual measurement head carried by the linear air-bearing granite column (see Fig. 1). The beam is in coincidence to rotation axis of the rotation air bearing and with the linear air bearing it is stable in its adjustment.

Therefore the orientation of the low coherent interferometer-axis is well known and the sample axis can be aligned for an optimized measurement. These conditions ensure that exactly the lens center-thicknesses are measured by the low-coherence interferometer [2].

Live centering of elements

The observation of the centering state with the autocollimator is suitable and typically used for live position-tracking and fast element alignment.

If the cross image from the autocollimator is focused to the upper center of curvature, the position of the cross hair on the CCD camera gives the real position of the surface.

During the lens stacking, the rotation axis of the air bearing is an excellent reference for the assembly as it is stable in time, at all heights and for all lens elements.

As described before, the rotation axis is automatically determined and displayed after one revolution. Therefore, the procedure is to put the lens on top of the previously centered lenses, focus into the center of curvature of the upper surface, determine the rotation axis by one revolution and center the lens.

After the centering the low-coherence interferometer easily reveals the air gap between the upper and the second lens, because all lens elements are centered to the rotation axis which is the measurement axis of the low coherence interferometer. This method makes the lens stacking easier, faster and at the same time very precise.

Automated lens-to-mount alignment

An additional option is to use the centering error-measurement to align lenses with respect to a mechanical reference, e.g. a mount. Figure 4 shows a photograph of an automatic setup for the exact lens-to-mount centering. The setup is equipped with mechanical or optical distance sensors and three high-precision actuators mounted on a separate vertical stage to access and align every single lens element inside of the assembly. The full travel of this stage is 1500 mm.

The distance sensors are used to determine the orientation of the mount tube in space during one revolution. For every lens element, the displacement between the center of curvature and the location where the calculated housing penetrates the image plane (of the center of curvature image) is determined.

For the automated alignment of the lens the stage three actuators push the lens precisely to this point in order to ensure a minimized center-

ing error with respect to the mechanical axis of the mount. This positioning procedure of the lens can be live monitored during the alignment. The actuators are stepper motors or piezo actuators with a force of 600 Newton per actuator. Additionally, this bonding unit is equipped with a dispenser for glue and UV light sources.



FIGURE 4: *Precise lens to mount centering with three automatic actuators.*

In summary, the presented instrument concentrates unique high resolution measurement instruments and procedures that allow the user the precise, fast and fully automated assembly of large wafer steppers-optics and a very accurate characterization of the whole lens.

REFERENCES

- [1] J. Heinisch, E. Dumitrescu, S. Krey, Proc. SPIE. 2006; 6288: 62881.
- [2] P. Langehanenberg, E. Dumitrescu, J. Heinisch, S. Krey, A. K. Ruprecht, Proc. SPIE. 2011; 7926: 79260E.
- [3] J. Heinisch, S. Krey, and E. Dumitrescu, Patent DE 10 2004 029 735

CLOSED LOOP THERMAL CONTROL OF A LITHOGRAPHIC OPTICAL COMPONENT

Rudolf Saathof¹, Aleksandar Haber², Jo W. Spronck¹, Michel Verhaegen²,
Robert H. Munnig Schmidt¹

¹Precision and Microsystems Engineering- Mechatronic System Design

²Delft Center of Systems and Control

Delft University of Technology, Delft, The Netherlands

Abstract

In EUV lithography the high throughput and high absorption can cause thermal deformation of the mirrors, which induces image distortion. In a previous paper [1] we have presented an actuation mechanism that is suitable to compensate and correct for these thermal aberrations. In this paper we present a closed-loop control strategy to apply it on this actuation mechanism and its application on an experimental set-up.

INTRODUCTION

Three important topics in optical lithography are the simultaneous performance on high throughput, image quality and overlay while it is widely known that these topics have a rather contradictory than a complementary character. In this research project we focus on the compromise between high throughput and image quality, where we look at the optical system. As part of Moore's law with decreasing cost per active element, the cost of ownership of a lithography tool needs to be as low as possible. Amongst others, this can be achieved by tools with a high throughput, realized by fast stages, high transmission optics, high sensitivity resist and high power light sources. Furthermore, Moore's law also drives the improvement of resolution resulting in optical systems with high numerical apertures, enhancing the imaging process using off axis illumination, phase shifting masks and optical proximity correction and decreasing the wavelength [2], which motivates the use of Extreme Ultra Violet (EUV) light [3]. Since EUV light is absorbed by all materials reflective instead of transmissive optics is used. Still, the mirrors absorb radiation, decreasing the optical transmission significantly, which demands an even higher light source power. Additionally, this absorption causes a local increase of temperature of the mirrors, which causes them to deform accordingly. These deformations result in wave-front errors, which can cause image degradation like image blurring and distortion [4].

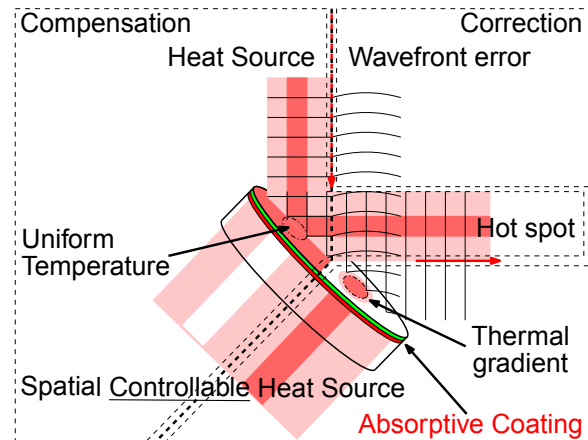


FIGURE 1. Active mirror concept: An absorptive coating absorbs radiation from a spatially controllable heat source. The compensation aspect of this actuation concept exposes an irradiance profile opposing to the heat source profile, creating a uniform temperature. The correction aspect is based on the principle of thermal expansion; thermal gradients cause local deformations. These deformations correct the wavefront error from other components in the optical system.

In this project we aim to correct for these aberrations, by means of an adaptive optics system. In traditional adaptive optics systems, actuators are mounted between a reference frame and the deformable mirror [5]. Because vibrations originating from the environment can excite the mirrors through this reference frame, they have to be avoided. Furthermore, mounting actuators may induce mechanical stresses which can lead to creep. Therefore, we studied a contactless thermal correction mechanism [1], where a radiating heat source with a spatially distributed irradiance pattern actively heats up and deforms the mirror surface as shown in Figure 1. The first aspect of this active mirror concept is actively applying an irradiance pattern opposing the predicted pattern from the lithographic process. This results in a uniform temperature distribution, which elim-

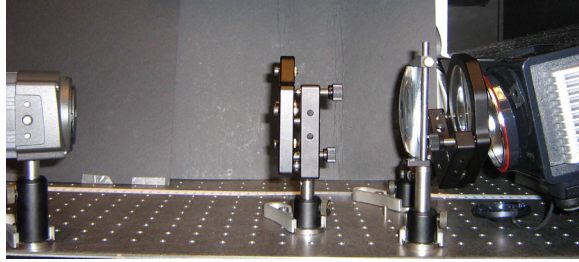


FIGURE 2. *The experimental set-up consisting of a thermal camera (left), a glass substrate with an absorptive layer (centre) two lenses to project the irradiance from a projector (right).*

inates the aberration caused by this active mirror, defined as compensation. Second, residual wave front aberrations are corrected by using the thermal expansion of the substrate material. By applying local temperature differences, the surface will locally deform, defined as correction. The integration of these two functions is realised by applying an absorptive layer on the mirror substrate, and on top of this layer a reflective coating is deposited. A spatially controllable heat source is used to expose the absorptive layer with a certain desired irradiance pattern. In this manner the actuation can be applied from the backside of the mirror, while influencing the front side of the mirror.

However, previously only open-loop experiments have been done [1], in which only limited accuracy is acquired. Restrictions of the accuracy are first, the thermal conductivity in the substrate material, so the heat input on one point on the mirror substrate is influencing the entire substrate. Second, the prediction of the disturbance caused by the EUV light may have limited accuracy, and its correction may be incorrect. Third, there is disturbance by parasitic irradiance patterns, which consist of a non uniform heat exchange caused by an environment which has a non-uniform temperature distribution. Therefore, we want to apply feedback control on the active component. In this paper feedback control is applied on the thermal distribution and consists of three experiments: the active component is kept at a homogeneous temperature to prove the compensation aspect; a step response is used to see the speed and a thermal profile is imposed to prove the correction aspect of the active mirror.

EXPERIMENTAL SETUP

In order to realise a control strategy in real time, an experimental set-up is built, which is shown in

Figure 2. The set-up consists of a BENQ SP870 5000 ANSI lumens video projector, a Bk7 glass substrate of 50×50 [mm], a FLIR A315 thermal camera and a computer. The projector acts as the spatially controllable heat source and has a total maximum optical power of about 1.5 [W] and projects a grey scale Matlab figure. Because the projector has a gamma γ correction, the relation between the grey scale value of the exposed pattern u and the irradiance Q is exponential by $u^\gamma = Q$, this non-linearity is compensated by $u = U^{\frac{1}{\gamma}} + 0.5$. In this relation u can vary from 0 to 1.

Two lenses are used to project the irradiance profile on the glass substrate close to the video projector, which results in a smaller picture, but a higher irradiance. The glass substrate has an absorptive coating that absorbs the irradiance originating from the projector. This is a broad-band coating for visible light, which absorbs 96% of the incident light. Before doing experiments, the substrate is brought to a steady state temperature, higher than its environmental temperature by exposing it with half of the power of the projector to enable cooling as well as heating. The temperature of the glass substrate is measured using the thermal camera and its measured data is processed in the computer with Matlab 2011a, using the image processing toolbox.

A checker-board pattern is used as an alignment tool, to align the video projector and the thermal camera. This alignment is done by physically moving the hardware and by adjusting settings in the software. The irradiance pattern exposed to the substrate is a Matlab figure, which can be placed arbitrarily in the projection of the video projector. Furthermore, the area of interest on the thermal camera is 160×160 out of 240×320 pixels, which can easily be shifted over the thermograph. This number of pixels is convenient for choosing different numbers of grid-points, which consist of sectors in the area of interest. In this sense, the size of the exposed Matlab figure is of more importance than the exact location. This flexibility is however limited, since it is desirable to cover the largest possible area of the video projector, since it increases the amount of used power.

The imaging processing is depicted in Figures 3 and 4. First, when the substrate is in its thermal equilibrium as described before, a reference ther-

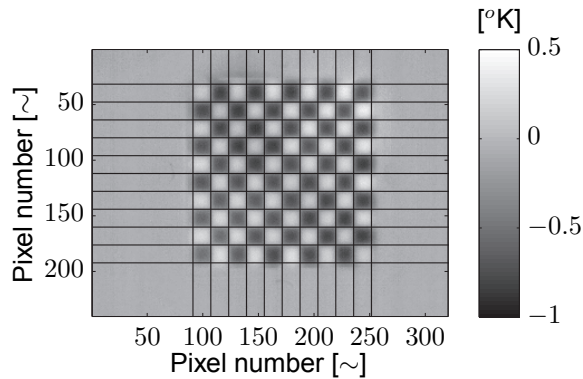


FIGURE 3. A checker-board pattern is exposed to the glass substrate as a tool for alignment. This thermograph is made by the thermal camera. The set-up is aligned, such that a complete picture takes 160×160 pixels.

thermograph is taken, consistent of the mean value of 25 thermographs, which is subtracted from each following measurement. Second, flickering of the whole thermograph is observed. As a stable temperature reference, an aluminium block is placed on the left side in Figure 3, covering the not exposed area between pixel numbers 1 and 50. The average temperature of the aluminium block is subtracted from the total image, which removes the flickering of the thermograph. Third, the area of interest in the thermograph is selected. Fourth, a grid is defined, which is shown by the lines in Figure 3, which defines the sectors of interest. Fifth, the average temperature of the individual sectors are taken, which function as the sensor signals for control. This spatial averaging is used to suppress the noise level of the thermal camera. The result of this image processing is shown in Figure 4.

The control loop is closed according to Figure 5. For this purpose the processed thermograph is compared with the desired image. The difference or error is used to apply the control algorithm as explained in the next section. Then a Matlab figure is projected on the glass substrate, containing the control irradiance, which heats up the substrate. Because the image processing and the control actions must happen within the sample time, we kept track of the time taken by the process. Because the thermal process is slow, the sample time can be chosen low, which is advantageous; imaging processing usually is time consuming. For a grid of 10×10 sector-points pre-processing of the data costs 3 [ms], which mainly consisted of spatial averaging of the ther-

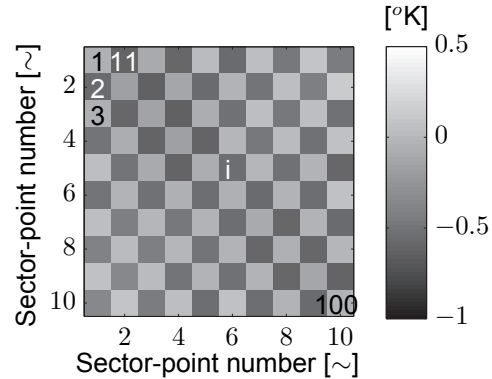


FIGURE 4. The raw data of the checkerboard pattern in figure 3 is processed to obtain this figure. This image is used for determining the contrast, which is the temperature difference between the sectors. These sectors are for control, in which they act as the sensor signal.

mographic data. The total loop time except acquiring the data, is 15 [ms]; the sampling time itself was 267 [ms]. This indicates that processing time is sufficiently small relative to the sample time to extend the control algorithm, or apply a denser time or spatial sampling.

CONTROL STRATEGY

Consider Figure 5 for the control strategy. By projecting a Matlab figure with the projector, the irradiance distribution Q can be controlled, and is exposed to the glass substrate GS . The irradiance is absorbed by the absorptive layer on the glass substrate, which heats up locally and gets a distributed temperature T . The temperature field causes emittance of infra-red IR radiation, and is captured with the micro-bolometer in the thermal camera. The glass substrate is heating up in a distributed sense; exposure of one point on the glass substrate will influence the entire glass substrate. This influence is weaker for points further away from the exposure of light.

The reason to apply closed-loop control is to reject disturbances d . These are due to the lab environment, which is temperature and moisture controlled, and therefore there is an airflow. Furthermore, the video projector is creating heat, which causes thermal gradients in the air. Additionally, there is a convective heat-flow, caused by the heating of the substrate, that transports heat from the bottom in the x-y plane of the substrate to the top, causing the upper side to be warmer than the bottom. The thermal coupling in the glass substrate is not taken into account; and the intensity

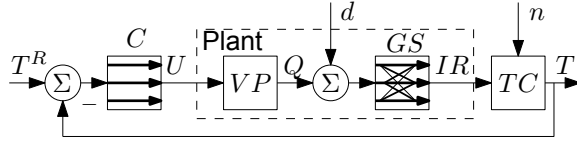


FIGURE 5. The closed loop system schematically. The reference is assigned as T^R , the controller C , which gives the control signal U to the video projector VP , which exposes the glass substrate GS with a irradiance Q and a disturbance irradiance d . This substrate heats up and emits Infra Red (IR) light, which is measured by the thermal camera TC , which has some noise n and is sent to the computer as the output signal T . In the controller and the glass substrate, arrows indicate the coupling: the controller has no coupling, but the substrate has. Three channels are shown; the thicker the line, the stronger the coupling.

of the video projector is not exactly uniform, which also needs to be taken into account. Finally, the performance of the control is limited by the sensor noise n .

To define the control strategy, a control grid has to be defined as shown in Figure 4. For that purpose the glass substrate is partitioned in 100 sectors, assigned with a number, which are Single Input, Single Output (SISO) controlled using Proportional Integral (PI) controllers in Matlab. These controllers have the following form:

$$u_i(t) = k_p e_i(t) + k_i \int_0^t e_i(\tau) d\tau, \quad i = 1, \dots, 100 \quad (1)$$

where $u_i(t)$ is the actuator signal at time instance t at the i^{th} sector, $e_i(t) = T_i^R(t) - T_i(t)$ is the error, in which $T_i^R(t)$ is the reference temperature and T_i the measured temperature; k_p is the proportional and k_i the integrative gain. By discretising Equation 1, the discrete-time PI-controller is obtained [6]:

$$u_i(m) = u_i(m-1) + (k_p + k_i T_s) e_i(m) - k_p e_i(m-1), \quad (2)$$

where $i = 1, \dots, 100$, $m = 1, 2, \dots, M$, m is the discrete time instance and M the last time instance.

EXPERIMENTS

In order to choose effective spatial sampling, the first experiments were to determine the noise on

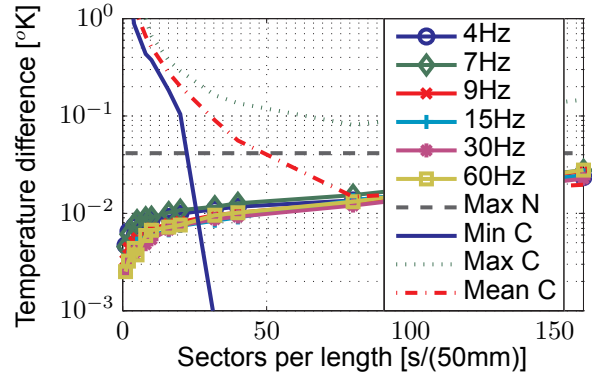


FIGURE 6. This graph is used to determine a suitable number of sectors. The lines with the marks indicate the noise level of the thermal camera. In order to decrease the noise level below the NETD of the camera of 45 [mK], indicated with the dashed line, the thermograph is spatially averaged. This is done for the various sample frequencies of the thermal camera, to see whether the noise is sample frequency dependent. The number of periods is also used to determine the attainable contrast. The contrast is determined, by exposing the substrate with a checker-board pattern and defined as the difference in temperature of neighbouring sectors. The minimal contrast should not be lower than the noise level in order to expose a thermal profile accurately.

the thermal camera and the attainable contrast. The results of these experiments are shown in Figure 6. First, different sample frequencies are used to see whether the noise level is related to the sample frequency of the thermal camera. Furthermore, the spatial sampling is also altered to see the effect of the applied spatial averaging. It is observed that the noise level is lower when less spatial samples are taken, as is expected. Second, the achievable contrast is dependent on the alignment, the power level of the video projector and the uniformity of the video projector over time and space. In this paper the contrast is defined as the temperature difference between neighbouring sectors, when a checker-board pattern is exposed to the glass substrate, see Figure 4. Three levels of contrast were obtained; a minimum contrast, a mean contrast and the maximum contrast. When the noise level of the thermograph is higher than the attainable contrast, the contrast will disappear in the noise. Therefore, this three different contrast values give the realisable contrast using closed loop, and the potential improvement of the set-up.

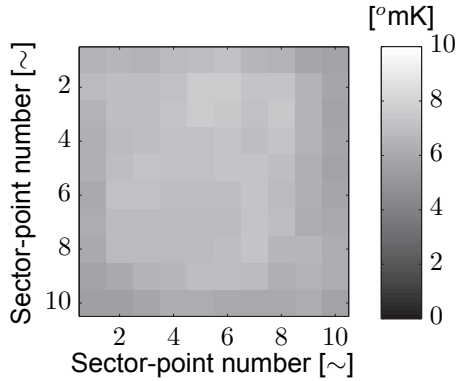


FIGURE 7. The accuracy of the thermal profile is limited by the noise level of the thermal camera. This graph shows the RMS of the residual noise during control of the glass substrate. In this graph the maximum RMS value is 7.6 mK, which corresponds to the measurement presented in Figure 6.

Three different closed loop experiments are carried out: in order to fulfil the compensation aspect of this active mirror concept, the mirror surface is controlled to have a uniform temperature, which reveals the control accuracy. In this experiment the RMS value of the error is observed. Additionally, for the correction aspect the speed of the controlled system and the ability to create a certain distributed thermal profile is relevant. First, the substrate is heated with a spatial distributed irradiance. After 35 [s] of exposure, the substrate is controlled to have a homogeneous temperature. Second, the mirror is controlled to the reference image in Figure 10. This closed loop result is compared with an open-loop experiment as shown in Figure 9, where this reference pattern is directly exposed to the substrate. In all the experiments a k_p and a k_i of 2.5 are used.

RESULTS

First, the performance in terms of static noise suppression is presented. Consider Figure 7, which shows the RMS error during control, over 1024 samples. In this graph the RMS error is 7.6 [mK] with a grid of 10×10 sectors and for a 20×20 sectors the maximal RMS value of the error was 10 [mK]. The residual noise level is equal to the noise level of the thermal camera. So by improving the performance of the thermal measurement, the thermal error can be suppressed further.

Second, the substrate is exposed to a irradiance and cooled down to its equilibrium state with a irradiance pattern as the Reference in Figure 10.

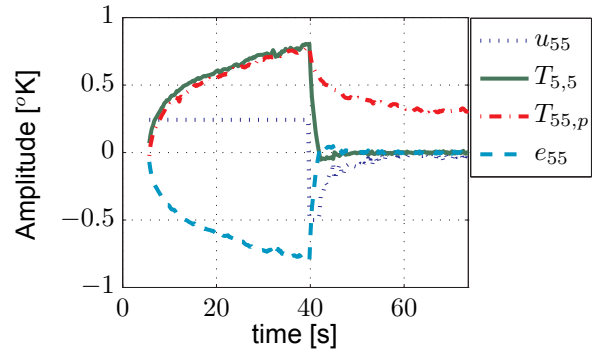


FIGURE 8. This figure shows that the temperature can be rapidly brought to a desired temperature using a PI control strategy. The passive behaviour of heating up and cooling down on sector no. 55 on the substrate is indicated by $T_{55,p}$. In the closed loop experiments, a rapid cooling is shown by T_{55} , u_{55} indicates the input, and e_{55} is the residual error.

Initially, it is heated and cooled down passively, and next actively with the control strategy, to have a fair comparison. Figure 8 shows how the temperature difference develops over time for one sector on the substrate. The passive behaviour is similar to an RC circuit as is expected. By the active control strategy the time constant decreases a factor of 10.

Third, as shown in Figure 9 and mentioned before, disturbances deteriorate the possibility to do open-loop control. The main causes for the errors shown in Figure 9 are the absence of an inverse model, which is still under development; and non-uniform heating, caused by the uniformity of the projector and heat transport caused by convection due to the increase of the substrate temperature. The control of a desired thermal profile, is compared with the current open-loop version. This results in a measured ΔT shown in Figure 9. What is shown in the figure, is that the error is as small as measured before in Figure 7. Furthermore a small gradient shows up in the actuator input. Additionally, in the actuation signal, there is a pattern, which has its similarities compared to the measured temperature in Figure 9, which clearly indicates the need of an inverse model.

DISCUSSION AND CONCLUSIONS

In this paper the feasibility of a feedback control consisting of 100 simultaneous SISO, PI controllers on the thermal distribution on a glass substrate is shown. This is a step in the development of an adaptive optics system suitable for

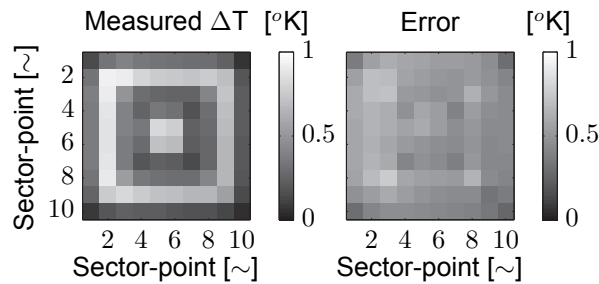


FIGURE 9. This figure shows the open-loop behaviour when the reference of Figure 10 is used as an input. Because of the conductivity of the material, the heat leaks away from one sector to the other. Therefore, we see some typical phenomena in the sectors diagonal to the corners of the squares.

EUV Lithography, to correct for thermally induced aberrations. We proposed an active mirror concept based on the principle of thermal expansion. First, the experimental substrate is controlled to have a uniform temperature, to prove compensation of the thermal impact on the active component itself. In this paper we showed the feasibility of this, by controlling the surface temperature with an RMS of 7.6 [mK]. This level of accuracy is limited by the performance of the thermal camera. Second, we showed that if undesired thermal differences exist, they can be rejected within seconds. The speed of correction is related to the power of the spatially controllable heat-source, the sampling time and feedback gains. And third, we showed that it is possible to accurately control a non-uniform temperature distribution, which corresponds to a certain mirror deformation. In the future course of this project this deformation will be precisely measured.

ACKNOWLEDGEMENTS

The Dutch "Pieken In de Delta" is acknowledged for supporting this research project and TNO for making the absorptive coating.

REFERENCES

- [1] Saathof R, Spronck JW, Munnig Schmidt RH. Evolving research on a non-contact adaptive optic actuation method for wave-front correction. In: Proceedings of the 11th euspen International Conference. Como, Italy; 2011. .
- [2] Mack C. Fundamental principles of optical lithography: the science of microfabrication. Wiley-Interscience; 2008.

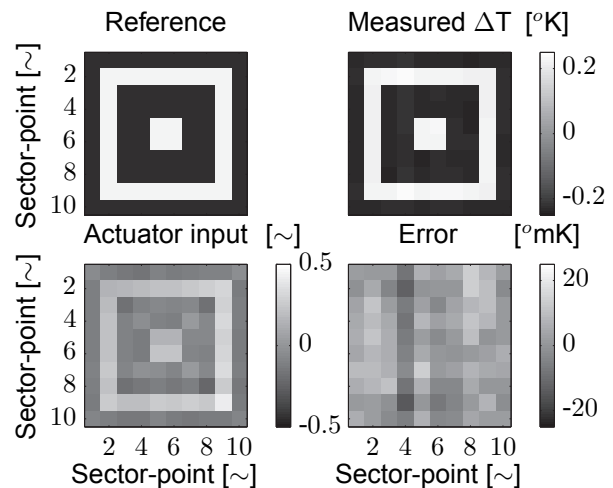


FIGURE 10. Instead of controlling a surface to have no temperature differences, the temperature can also be controlled to a certain desired thermal distribution. This is realised by closing the control loop. This set of figures is obtained in steady state. The measured ΔT is very similar to the Reference, which is also by the error, which shows no clear correlation with the Reference. What is also shown is the actuator input; in order to get the square at a uniform temperature, the lower corner right needs more intensity. This is due to the inhomogeneous irradiance from the video projector.

- [3] Bakshi V. EUV lithography. SPIE-International Society for Optical Engineering; 2008.
- [4] Spence PA, Gianoulakis SE, Moen CD, Kanouff MP, Fisher A, Ray-Chaudhuri AK. System performance modeling of extreme ultraviolet lithographic thermal issues. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures. 1999;17:3034.
- [5] Roddier F. Adaptive optics in astronomy. Cambridge university press New York;; 1999.
- [6] Aström KJ, Wittenmark B. Computer-Controlled Systems: Theory and Design. Dover Pubns; 2011.

DESIGN AND VERIFICATION OF A COARSE STAGE OF PLANAR MOTOR LEVITATING BY AIR BEARING

Zhigang Zhang, Liwei Wu, Xiaowen Zhang, Feng Chi, Jianrui Cheng
Shanghai Micro Electronics Equipment Co.,Ltd

INSTRUCTIONS

Planar motors have been used in IC machine tools for manufacturing, inspection and assembling, and we think it can be also extended to FPD or LED field. The planar motor has an advantage in that the motor occupies a small area and the system can be compact in contrast to systems using multiple linear motors.

The main types of planar motors used are sawyer motors, synchronous permanent-magnet planar motors (SPMPM), and induction planar motors. Among them, Sawyer planar motor based on variable reluctance principle suffers from inherent cyclic errors and heating problems, thus high force density and high accuracy constrains by its principle. SPMPM planar motor can generate both driving and levitating forces, has been widely used in high performance exposure stage design. But consuming power continuously to suspend the weight of the moving platform, it generates heat which deforms mechanical structures and changes properties of actuators or sensors. The cooling problem is hardly to solve. Basically, more than six high precision sensors are needed because maglev stage should be controlled in six degrees-of-freedom. And often it requires a nonlinear control algorithm to compensate nonlinear behavior of levitating mechanism. And for safety reason, levitation control is critical due to crash may occur between the mover and the stator, or between project lens and the stages in lithograph tools.

In this paper, we present a coarse stage containing a novel planar motor based on 2-D Halbach array in combination with a 2-D coil arrays, it has following features: (1) Levitated by air bearing, so control design is more simple, and much more load mass is not seriously in contrast to magnet levitation, for example, it can be easily extend to use in 450mm wafer stage. (2) Novel planar motor. (3) Hall sensor array for stage initialization, motor commutation, and error state recovery.

STAGE PRINCIPLE

Fig.1 shows the concept of this moving stage containing a novel long-stroke planar actuator.

The exposure stage equipped with 4 Z-air bearings so that it can float horizontal over the base plate. The planar actuator propelling the stage in X/Y/Rz direction can be classified as an unrolled AC synchronous permanent magnet motor, which is composed of a stationary magnet array and a moving stage carrying coil arrays. For power efficiency and low field distortion, a new Halbach magnet array is used. There are four coil sets in the air gap, two coil sets are used for driving the x-direction and the other two for y-direction perpendicularly. The length and width of the coil should be chosen carefully in the SPMPM, because the magnet array is a 2-D one. The stage uses Hall Effect sensors for initialization before other position sensor signals are valid. At each corner, a hall sensor array PCA is equipped. In the middle, there are water distribution unit and motor connect PCA.

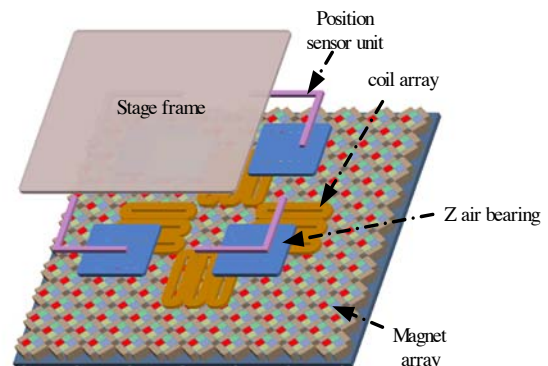


FIGURE 1. Moving stage concept

MAGNET ARRAY

Fig.2 shows a NdFeB-magnet array that is used for the planar motor. The arrow denotes the magnetization direction of the permanent magnet. The magnet array includes combine magnet units and transverse magnets aligned to two dimensional array. The combine magnet unit includes a first diagonal magnet, a second diagonal magnet, a third diagonal magnet, and a fourth diagonal magnet that cooperate to provide a combined magnetic flux. further, each diagonal magnet can be generally rectangle shaped and the diagonal magnets are arranged together in the shape of a parallelepiped. Each combine

magnet unit is similar design. This leads to strong magnetic fields above the magnet array and strong force generation capability. as a result thereof, the planar motor can move the stage and a work piece with improved efficiency.

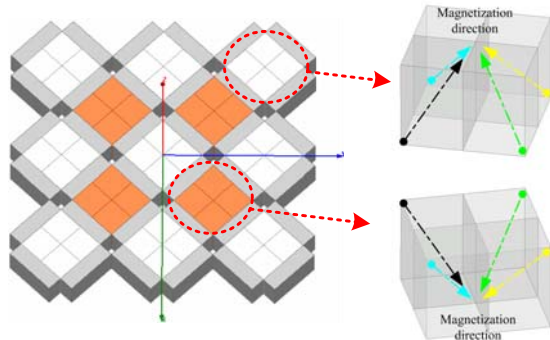


FIGURE 2. 3-D Magnet array (patent pending)

The entire magnet array was assembled into base plate and filled with epoxy resin. Air bearings, which are critical in providing the levitation for the stage, require a very good surface finish of $\pm 10\mu\text{m}$. To achieve this over the whole magnet array was a big challenge. After the finishing was completed, the entire surface was flat. The epoxy after machining has small pores. So to get the good finished surface of known thickness for the optimum performance of the air bearings, mirror finished aluminum sheet with surface roughness of $0.1\mu\text{m}$ is placed over the entire base plate. several adhesive tapes were used to fix the sheet to the base plate to prevent the aluminum sheet from warping.

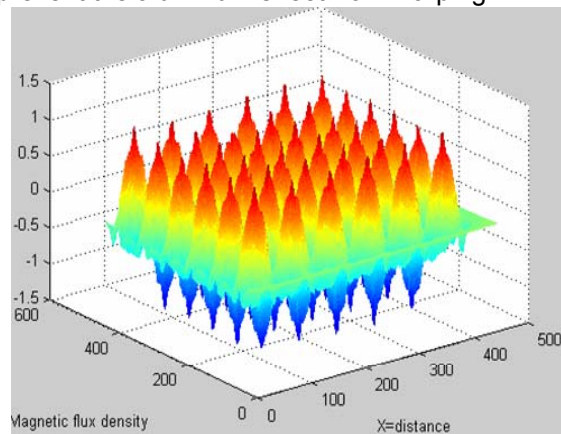


FIGURE 3. Magnetic flux density in z direction

The magnetic flux density distribution is predicted with FEM software and expressed in the global coordinate system. Figure 3.8 shows the B_z components of the magnetic flux density distribution of the magnet array. which is a sine

wave in both the x- and y-directions. the B_x component of the magnetic flux density distribution is a sine wave in the x-direction and the B_y component of the magnetic flux density distribution is a sine wave in the y-direction. The peak value of flux density is 1.22T while the air gap is 3mm.

COIL ARRAY

The planar mover has four sets of three-phase systems with coreless concentrated winding. Figure 4 shows a set of three coils with current conductors R, S and T, the pitch of which being approximately $5\tau/3$ between the coils. We defined τ as the pitch of magnet array. All of the coils are fed by a three-phase current system. For the same direction force exerted on the current conductor, the current poles of winding r+, s+ and t- will be connected.

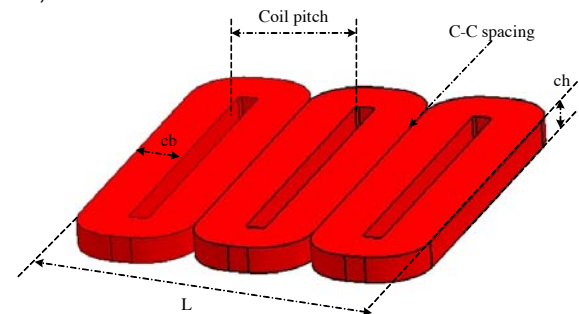


FIGURE 4. 3-phase coil array (pitch = $5/3 \cdot \tau$)

FORCE AND TORQUE PRODUCTION

Linear material properties and rigid body dynamics are assumed. As a result, the superposition principle can be applied to force and torque calculations. Using FEM models, the force and torque in large planar actuators with various magnet-array configurations and with concentrated windings can be predicted.

For contrast, another type of magnet array proposed by J.C.Compter[1] was calculated at the same time. When the same coil travels to different position above magnet arrays, the force constant can be obtained in Figure.5(a). as same magnet array pitch is applied, the peak force is 40.5N/A for J.C.Compter magnet array. and peak force is 44.3N/A for magnet array presented by this paper.

Figure.5(b) shows the simulation result for different coil type. For contrast, the same type of $0.16 \times 2.5\text{mm}$ rectangle wire was used. when $5\tau/3$ coil pitch is applied, the peak force is 44.3N/A, while when $4\tau/3$ coil pitch is applied, the peak force is 35.17N/A. Thus, higher force constant and higher motor steepness can be

obtained by the coil array type presented in this paper.

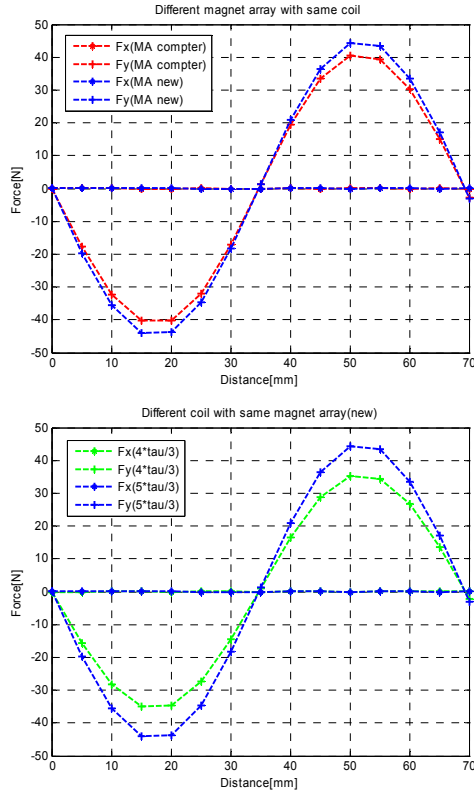


FIGURE 5. single coil force calculation (a) different type of magnet array (b) different coil

POSITION SENSOR

Normally, the horizontal position of planar motor was controlled by interferometer, but at some special instance, another position sensor must be needed. Figure 6 indicated a position sensor unit which is based on sensing the magnet field with Hall sensors. As shown in Fig.1, there are four sensor unit located around perimeter of the planar motor as a 2-D encoder, for measuring the relative position between magnet array and coils array, which can use for commutation of coils current and stage initialization, and error state recovery. each position sensor unit includes five hall sensors, and the pitch of which is $2\tau/3$ between the sensors.

Using simulation result of magnet array, this position sensor principle can be checked in Mat lab, The accuracy is mainly determined by the offsets and gain errors of the Hall elements and comparison indicated that an absolute accuracy of 0.3mm is realistic when magnet array pitch is 36mm, as shown in Figure.7.

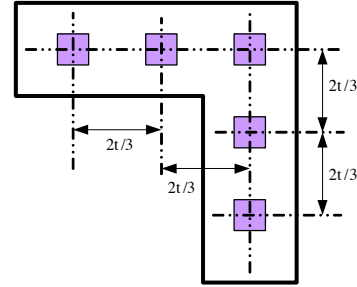


FIGURE 6. Hall sensor PCA

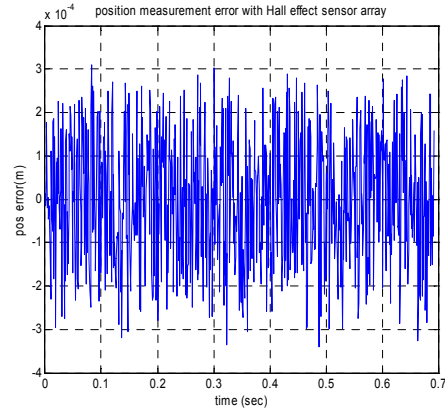


FIGURE 7. Position sensor errors

Z- AIR BEARINGS

The dynamic performance of the moving stage is strongly affected by the air bearings. The fluid film of air bearing is achieved by supplying a flow of air through the orifice into the bearing gap. So the dynamic parameters include air gap, stiffness, payload and so on, which are used to optimize the bearing for particular applications.

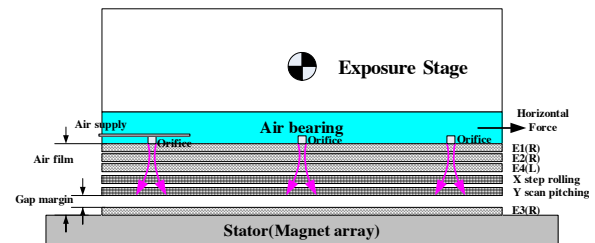


FIGURE 8. design concept of air bearing

There is a distance between the center of gravity (COG) of moving stage and the planar actuator. So an off-center load is accelerated, a large torque R_x/R_y is applied to the moving stage. This might effect air gap of moving stage. Fig.8 shows the concept of air bearings. It must consider for air film that flatness of bearing part surface(E1, $1\mu\text{m}$), air bearing assembly(E2, $2\mu\text{m}$), air bearing structure deformation(E3, $2\mu\text{m}$)

because of preload, local flatness of stator surface (E_4 , $2\mu\text{m}$), X step rolling and Y scanning pitch of moving stage may affect air gap of bearing.

When the stage is moving in X-direction or Y-direction, the torque is given by $H \cdot M \cdot A$ about 58.8 Nm. Where H is the distance between COG and planar motor about 70mm, M is stage mass about 56Kg, A is acceleration of moving stage about 1.5g. And the torsion stiffness is about $6.75 \times 10^6 \text{ Nm/rad}$. So Air gap variation is $1.72\mu\text{m}$.

The total air film is designed to $15\mu\text{m}$ satisfied with the requirement of moving stage.

STAGE IMPLEMENTATION

A prototype of this planar motor design is being built and a controller fitted for three degrees of freedom is being built, tested and approved.

PROTOTYPE VERIFICATION

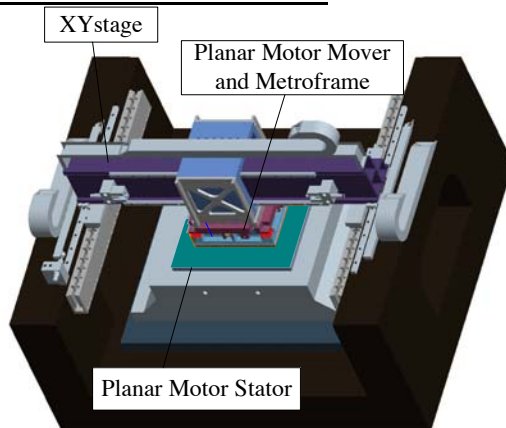


FIGURE 9. Planar motor verification

The tests was designed to verify the validity of the position sensor units and the calculation of the motor constant, the set-up given in Fig. 9. The planar motor is initially mounted under a gantry consisting of two linear motors driving the gantry in the y-direction and one linear motor for the x-direction. a six-axis force/torque transducer (DELTA type from ATI Co,Ltd) is mounted between the planar motor and the gantry. This set-up enables the verification of the predicted forces and torques and ensures that correct gain factors will be available for the 3-DOF control loops. At the same time, the position sensor units can be also verified compared with X/Y encoders in the gantry.

EXPERIMENT

The 3-DOF control loops are subsequently implemented by the experiment. Figure.10 gives the set-up of test bench. We use two three-axes of laser interferometers with sub-nanometer resolution to measure the position in the plane, and three channels of capacitance probes for the stage position out of the plane. Three laser triangle sensors(IL type from Keyence Co,Ltd) provide absolute X/Y/Rz measurements for initialization. The nominal air gap clearance between the magnet array and the mover is $250\mu\text{m}$. A digital signal processor (from dSpace Co,Ltd) is used as a real-time control processor to stabilize and control the stage. This control loops can be evaluated and inverted at sample rates of 2.5 kHz by the DSP system controlling the planar motor.

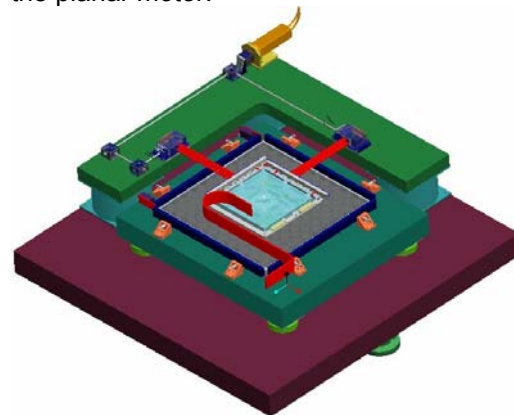


FIGURE 10. Stage control experiment

STATUS AND OUTLOOK

A prototype of coarse stage with novel planar motor is being constructed and verified, as shown in Fig.9 and Fig.10. As levitated by air bearing, Four 3-phase coil arrays together can control a load in three degrees of freedom. The stroke can be simply extended by applying a larger magnet array. More detailed analysis reveals that the planar motor can be more efficiency using the magnet array and coil array presented in this paper.

REFERENCES

- [1] J. C. Compter, "Electro-dynamic planar motor," Precision Engineering, vol. 28,no. 2, pp. 171–180, Apr. 2004.
- [2] J. W. Jansen, E. A. Lomonova, A. J. A. Vandenput, and J. C. Compter, "Design tool for a 6-dof planar motor with moving permanent magnets and standstill coils," in Proc. of the 4th international symposium on linear drives for industrial applications, Birmingham, UK, Sep. 2003, pp. 93–96.

FLEXURE-BASED MICROSCOPE OBJECTIVE

Christopher R. Stockbridge¹, Fatih H. Köklü², Euan Ramsay³, Yang Lu¹,
M. Selim Ünlü², Bennett B. Goldberg³ and Thomas G. Bifano¹

¹Department of Mechanical Engineering

²Department of Electrical Engineering

³Department of Physics

Boston University

Boston, MA, USA

BACKGROUND

Continuous reduction of feature dimensions in modern computer chips increases the challenge of measuring them. The state-of-the-art technology for imaging and fault isolation in integrated circuits (ICs) is done from the backside and uses a solid immersion lens (SIL) that sits directly on the back of the substrate to be imaged. A SIL can drastically increase the Numerical Aperture (NA) of the system and values of 3.5 are possible in silicon ICs. The physical placement of the lens requires high precision and good optical contact with no more than a 5nm gap under any portion of the lens. Commercial failure analysis systems require integration of the SIL with an objective system. This paper discusses the design of an integrated objective for imaging with an aplanatic SIL (aSIL).

INTRODUCTION

Precision landing and good contact of the aSIL on the substrate while maintaining its transverse position relative to the backing objective is critical for imaging. Maintaining the required positional tolerance is complicated by the fact that the aSIL must translate 3mm vertically to allow focusing while also providing a contact force of 10 ± 2 N against the substrate. Based on optical simulations using Zemax, the lateral tolerance in positioning of the aSIL must be less than 250 μ m in order that off-axis aberrations maintain a Strehl ratio of greater than 80%, close to the diffraction limit. The high magnification of the aSIL means that this lateral tolerance corresponds to a 16 μ m shift in the field of view, which becomes the limiting parameter for the transverse displacement. Within this tolerance, the optics perform close to the diffraction limit with a field of view that allows the user to accurately determine the position on the chip from one aSIL landing to the next. The same demagnification that lowers the X and Y

tolerance increases the required Z axis travel for focus.

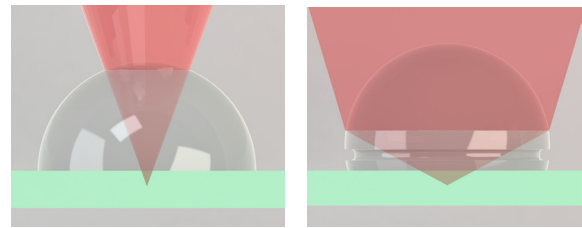


FIGURE 1. a Central SIL (left) has a much lower NA than the aSIL (right), even with the same backing objective.

The SIL used in this project is a super-hemisphere with a 4.70mm diameter. One side is polished to a plainer surface for a lens height of 2.92mm. Lenses are made out of either Silicon or Gallium Arsenide depending on the wavelength being used. Options for holding the SIL are extremely limited. As shown in Figure 1, a full 180° of the lens is utilized as an optical surface leaving a 500 μ m tall band around the bottom of the SIL as the only area available for an interface with the objective housing.

When holding the aSIL against a substrate, the system is sensitive to gaps on the order of 5nm in the optical contact area. Larger gaps will prevent good optical coupling especially for the high angle rays that provide the best resolution. In order to maintain this contact, the contact force must be at least 10N while also maintaining good angular alignment.

This system must enable use of an aSIL both on a laboratory optical bench and on a commercial fault isolation microscope, the Meridian-IV, built by DCG Systems.

OBJECTIVE HOUSING DESIGN

The overall design problem of the objective assembly was broken down into a few critical areas which each correspond to one component of the final design. This modular approach allows each element to be tuned for a different performance characteristic. The body, for example, allows focal travel and is stiff to off axis forces while the SIL frame must be rotationally compliant. A cutaway view of the assembled objective housing is shown in Figure 2.

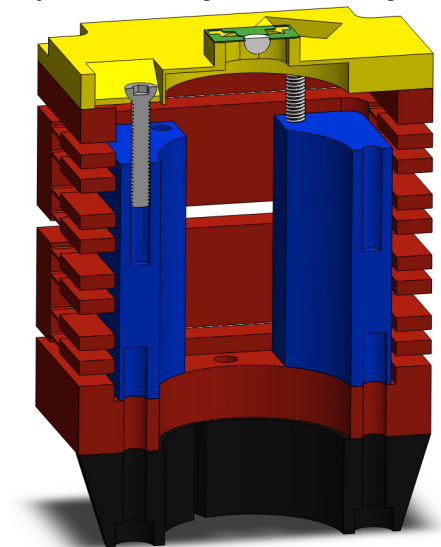


FIGURE 2. The assembled objective assembly is shown cut along the X,Z plane with the backing objective removed for clarity. The major components are: The aSIL lens is shown in white, top center. The SIL holder is in green, and the end cap is in yellow. The flexure-based body is shown in red. Preload components include both the blocks (blue) and the modified screws shown in grey. The objective collar is shown in black at the bottom of the figure.

The material selected for the objective housing is grade 5 titanium. Using this aluminum and vanadium compound gives the titanium higher yield strength, and a lower modulus of elasticity than heat treated steel which is ideal for flexure design. The high yield strength allows a greater displacement from a given element while the lower modulus of elasticity allows the material to be thicker when designing around a given spring constant. The thicker element is desired so that small manufacturing errors, especially on thickness of the flexure webs, have lower impact on symmetry of the device and the travel of the flexure elements. Titanium also has the advantage of resisting corrosion, which is

important in the dust sensitive environment of chip testing.

Flexure-Based Body

The flexure-based body is the main component of the objective assembly. It provides the necessary stiffnesses on all linear axes and constrains the motion in a smooth manner. This part is cut from a single block of titanium, so all manufacturing tolerances are determined by machining and not assembly accuracy.

The flexure body performs the tasks of maintaining a stiffness necessary to limit the X and Y travel while allowing focal travel along the Z axis. After considering several alternatives we decided to use a flexure-based system. Other similar objectives use a coil spring and linear bearing combination that have issues traveling in a fluid manner. We also considered an air bearing design, however the additional infrastructure requirement for each objective was not practical.

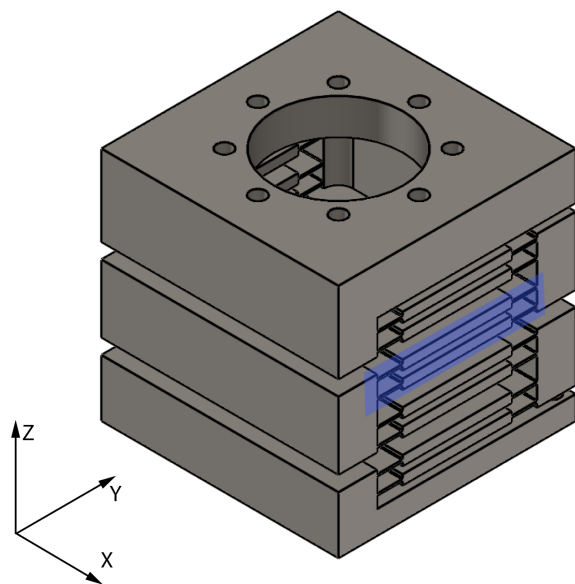


FIGURE 3. The flexure body is shown here with the opening for the backing objective visible at the top. The blue highlight shows one of the four pairs of flexures that acts as a four bar linkage and maintains a parallel relationship between two sections of the body.

The flexure design includes the necessary stiffness and compliance on the three primary axes and provides the necessary contact force for good imaging. Because of the magnification, a focal range of 3mm is required in order to

compensate for substrate thickness errors of just 20 μ m. The force is maintained at 10 $\pm$ 2N over this range.

This body primarily consists of four sets of four flexure arms. Half of one set is highlighted in Figure 3 to show how the independent sets are combined. Each set maintains parallel positioning across its length to the next block of the body. The sets are arranged in an alternating pattern so that any parasitic motion, caused by the long cantilevered flexures, will cancel out and produce a symmetric system. Notch flexures would produce more parallel travel, but at the cost of reduced travel for each flexure set. In the limited space available the longer flexure elements are the best available option.

By positioning the systems in series we are able to sum the displacements and increase the system travel while maintaining the key benefits of the flexure system.

Preload

Adding a preload mechanism increases the objective's performance by enhancing the imaging throughput and limiting motion as the microscope turret rotates. This enhances use of the SIL, and also limits disturbances to the overall system when other objectives are in use. Preload increases throughput by defining an accurate landing position and allowing automated landing procedures to operate more quickly. If a z-axis vibration is possible, as is the case with no preload, then the landing must proceed slowly through this entire vibration range. Preload effectively gives a hard stop to this vibration range and allows safe translation to this point. Additionally this hard stop provides a reference point so that any additional movement is adjusting travel within the focal range.

Turret movement as the microscope changes objectives causes a large impulse along the X and Y axes of the objective. This causes a large and well-sustained vibration, especially in the weaker X direction. Adding preload effectively stiffens these axes and reduces the Q of the system and eliminates disruptive vibrations. Internal vibrations remain but they have little or no impact on the imaging system.

Physical components of the preload system include 3 modified screws that have angled heads that fit kinematically into matching angled cuts on the end cap. Half of one of these angled seats is visible in Figure 2. The preload limits the flexure-based body to a range of 50-100% compression, and allow adjustment so that the SIL is level when it contacts the substrate.

SIL Holder

The aSIL holder must allow the aSIL to rotate about the X and Y axes in order to gain the best optical contact while utilizing a small contact area on the SIL. This is realized by using a 0.6 inch square frame cut from 8mil thick titanium shim stock. The design features a central hole that matches the diameter of the aSIL at a groove that has been cut in order to facilitate holding it. This supports the aSIL over 85% of its circumference and replaces the glue contact that is commonly used to hold other similar lenses.

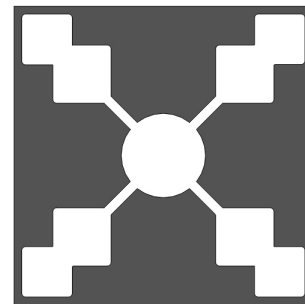


FIGURE 4. The SIL frame holds the SIL with 4 independent arms.

This SIL holder utilizes a groove cut in the SIL to minimize the contact area, and allow most of the lens surface to be preserved for optical use.

The frame enhances optical contact by allowing the SIL to self align with the substrate by rotating up to 5 milliradians with negligible translation along the optical axis under the 10N force required for imaging.

Thin corners of the frame allow additional flexibility while installing the brittle lens. This frame is installed by gluing it into place on the end cap, which fixes the relative positions of the cantilevered arms and locks the aSIL into place. This end cap screws directly into the flexure body, and has a center position defined by the angled cuts of the preload positioning system. By combining the end cap, aSIL and aSIL frame, the end user has a manageable part that can be replaced easily as the aSIL becomes worn or contaminated from use. This is planned to be a

consumable part when used in a commercial system.

Objective Collar

A split ring collar is used to connect the backing objective and the rest of the housing. This collar clamps directly onto the body of the backing objective and allows placement of the objective housing without changing the optical path beyond the objective. The clamped design allows adjustment of the force between the SIL and substrate by changing the placement of the housing relative to the backing objective.

Future Work

The primary issues with the current flexure design are related to interference with other mechanical components in the Meridian IV fault isolation microscope. The corners closest to the objective collar make this device difficult to install, especially with other large objectives already in use. Transitioning the flexure design to one with a round profile introduces additional manufacturing challenges and creates an uneven stress distribution on the bending elements which must be evaluated numerically.

We have elected to add an additional degree of complexity to the next phase of the design by adding flexures on a third side of the body. This set of flexures will stiffen the body along the X axis and will create a more uniform response in the X and Y directions. Stiffening this axis will also shift one of the two primary vibration modes to a higher frequency when no preload is applied.

Long term the round profile will also make the housing easier to seal. Waterproof sealing is not required for lab use, and short tests on resolution targets, however chips running at full speed typically require liquid coolant which must not pass through the optical path above the SIL.

DISCUSSION

The flexure-based system currently has several challenges and concerns about long-term use. The flexure body is 10 times stiffer in rotation along the flexure arms (Y axis) than it is about the X axis. This disparity in stiffness makes the system likely to vibrate about the X-axis when in motion and makes orientation significant when installed on a motorized turret. Adding preload and additional flexures to an adjacent side will mitigate this issue.

The fabrication method of using wire electric discharge machining (EDM) to define the flexures creates potential concerns about the product lifetime. Wire EDM produced very rough surfaces, which will adversely affect the fatigue life. As simulated in SolidWorks 2011, the peak stresses in the flexures are 300MPa when the body crashes to its fully compressed position. This should correspond to a product lifetime in excess of 10^6 cycles, however further investigation is needed.

CONCLUSION

A system has been designed and built that allows straightforward use of an aplanatic Solid Immersion Lens. This has greatly enhanced the laboratory use of these lenses by giving controlled and repeatable placement. It has also enabled integration and use of an aSIL in a commercial fault isolation microscope where free placement of the lens would not be possible.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the Intelligence Advanced Research Projects Activity (IARPA) via Air Force Research Laboratory (AFRL) contract number: FA8650-11-C-7102.

EXTENDING ALL-OPTICAL PROCESSES TO THE 11NM (20NM HALF-PITCH) TECHNOLOGY NODE

Rudi H. Hendel¹; John S. Petersen¹; David A. Markle¹;
Alexander K. Raub¹; Robert T. Greenway¹; Michael C. Smayling²

¹Periodic Structures, Inc.; Los Gatos, CA, U.S.A.

²Tela Innovations; Los Gatos, CA, U.S.A.

INTRODUCTION

The continuation of dimensional scaling for keeping the Semiconductor Industry progressing according to Moore's Law faces a multitude of challenges today. In addition to the need for introducing new materials (high-k/metal gate) and new device architectures (such as FinFET or TriGate), we have reached the limit of what is possible for optical lithography. Any further reduction in geometries either requires a reduction in wavelength (to 13.5nm: soft X-ray or EUV) or requires additional process steps (such as Sidewall Image Transfer) leading to added complexity and significantly increased costs.

The practical limitation for the resolution of optical exposure tools which presently operate at a wavelength of $\lambda=193\text{nm}$ and use water immersion is 40nm half-pitch, or 80nm pitch, and these dimensions are in use in or near manufacturing today. The problem at hand is to achieve the smaller dimensions required for future technologies reliably, in scale and above all, cost effectively.

THE 1-D DESIGN APPROACH

One of the means of managing complexity and cost is to simplify the complexity of pattern layout. The traditional two-dimensional layouts are being transitioned to a 1-D design which is based on a highly regular layout with one preferred direction. In the extreme case, the layout may call for a single line-dimension and a single line-to-line spacing – extreme regularity. This approach is called GRATE (Gratings and Trim Exposure) and is generally applied to critical interconnect metallization layers. The lines and space themselves do not contain design content and can be patterned with imaging technologies used to define gratings (such as interference-based lithography), significantly reducing the complexity of the optics of the exposure tool. Recently, increasing regularity has transitioned to the transistor level. A good example for this regularity is the Intel Trigate transistor targeted for the 22nm

Technology Node and the first implementation of a non-planar device architecture.

A tilted SEM showing this device architecture is shown in Figure 1.

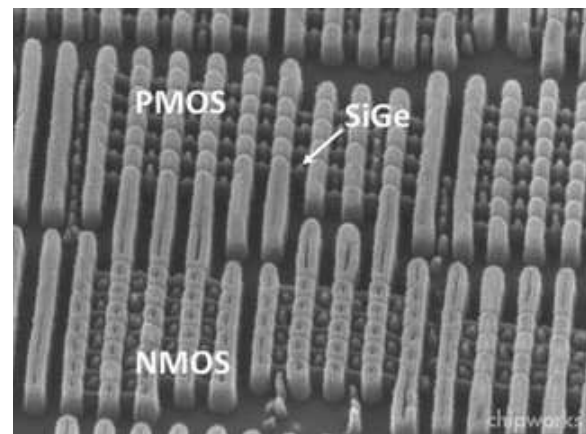


FIGURE 1. Tilt SEM Image of Intel 22 nm TriGate NMOS/PMOS Transistors [1] showing the high regularity of the layout, making the transistor layout conducive to GRATE-compatible patterning.

The segmentation of the required patterning within the GRATE approach into two independent exposures now allows the user to choose an optimized technology for each of the patterning components making up the composite image. Rather than being forced to make compromises necessary to accommodate the sometimes conflicting requirements for the entire pattern, it is possible to optimize the line-space pattern for minimum line edge roughness (LER) and minimum line width roughness (LWR) and optimize the personalization (the cutting of the line pattern) to its requirements.

The line-space pattern requires well defined line edges. Superior line definition (or minimum line edge roughness) is best achieved with the use of interference lithography (see Figure 2).

LWR through Focus

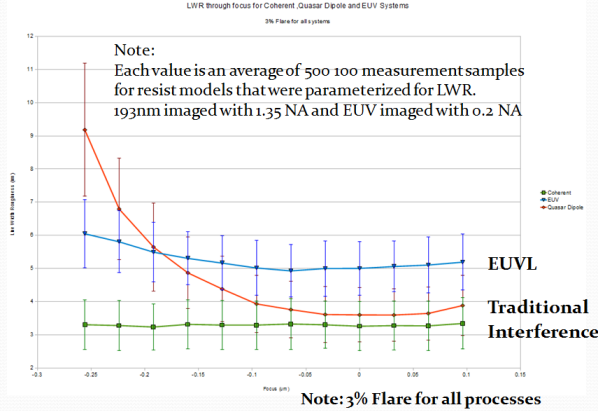


FIGURE 2. Prolith modeling of Line Width Roughness through Focus, comparing a variety of lithography implementation options, such as: EUV Lithography, Traditional Lithography and Interference Lithography. Each datapoint required 500 simulations, each containing 100 measurements made across a 300 nm sample region of an infinitely long line.

The line-space pattern, whose quality is critical for minimizing parametric variations (such as the variability of transistor on-current, transistor off-current or interconnect resistivity and variability which ultimately may impact device reliability) is often seen as easy to implement as it does not contain any design information. The design content is transferred to the final pattern through the line-cuts and line-to-line interconnects. The positions of such features are determined by automated and commercially available layout tools capable of transitioning a traditional 2-D design into a one-dimensional fabric [2].

On the wafer, such line-cuts can be formed by traditional lithography using masks [3] – however, the limitations of the lithography process require an increasing number of mask levels for a single metal interconnect level (up to five mask levels for a critical level interconnect in the 22 nm Technology Node) and are therefore very costly. Alternatively, line-cuts may be written directly on the wafer – without a mask (or maskless) using direct write technology and saving the cost of mask generation altogether. Traditionally electron beams are the preferred technology for maskless lithography. However, there are significant challenges remaining to be solved, such as the need to independently control millions of independent beamlets, to manage beamlet-to-beamlet interactions and to

achieve adequate system throughput. An optical approach for maskless patterning of wafers is highly desirable.

THE OPTICAL DEFINITION OF LINE-SPACE PATTERNS BEYOND THE RAYLEIGH LIMIT.

The resolution limit of an optical system is limited by the Abbe equation:

$$\text{Resolution Limit} = k_1 \cdot \text{N.A.} / \lambda$$

This minimum resolution is frequently referred to as the Rayleigh criterion. Here, k_1 indicates the capability of the imaging process and is limited to 0.25. Today's state-of-the-art processes achieve k_1 -factors of ~ 0.3 . N.A. is the numerical aperture of the projection system. Using immersion allows N.A. to exceed 1, and N.A. values of 1.43 are typically in use today. λ is the exposure wavelength. The exposure wavelength for present state-of-the-art lithography is 193 nm. The realistic resolution limit of systems with the above capabilities is 40nm, or 80nm pitch.

It is possible to extend this resolution limit beyond the Rayleigh Criterion by using Stimulated Emission Depletion (STED) [4]. STED has demonstrated exceptional resolution capabilities in microscopy and the same approach has been proposed for lithography [5], [6]. InSTED lithography superimposes an exposing beam at λ_1 with a depletion beam at a second wavelength λ_2 . The purpose of the depletion beam is to shunt the chemical reaction at the feature edge (Figure 3).

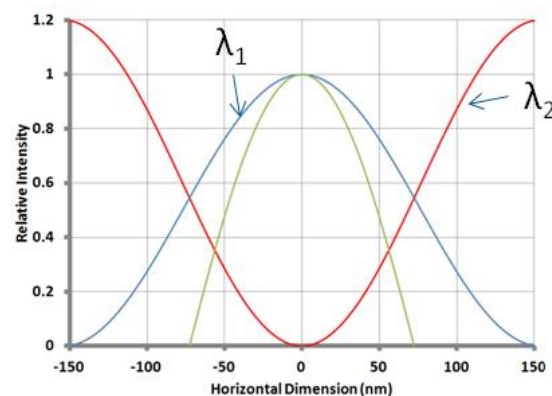


FIGURE 3. The exposing radiation at λ_1 is shunted at the feature edge by Inhibiting radiation λ_2 , resulting in a narrowed feature. The Line-width is thus driven by Quantum Mechanics (availability of transitions

between excited levels as well as the lifetimes of excited states) and is not set by Optical Limits (the Rayleigh criterion)

This effect reduces the feature dimension and sharpens the image contrast. The ultimate resolution of the pattern depends on the relative intensity of exposure vs. depletion beams and may reach below 10 nm (Figure 4)

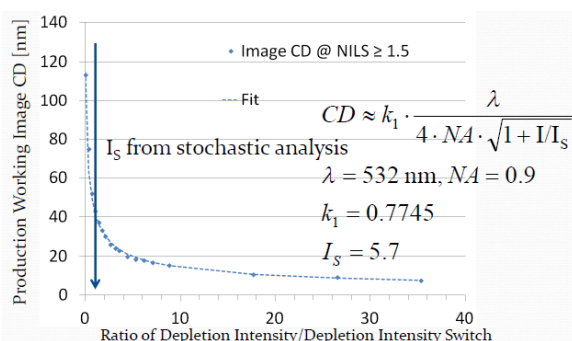


FIGURE 4. The final image CD of a feature defined with STED depends on the relative intensities of exposure and depletion beams and may reach below 10nm.

The pitch of the pattern remains determined by the Rayleigh Criterion and is not reduced by STED. Thus, if we expose an interference pattern using scanning beam interferometry with lines controlled by STED, we will see a sparse pattern of narrow lines (Figure 5).

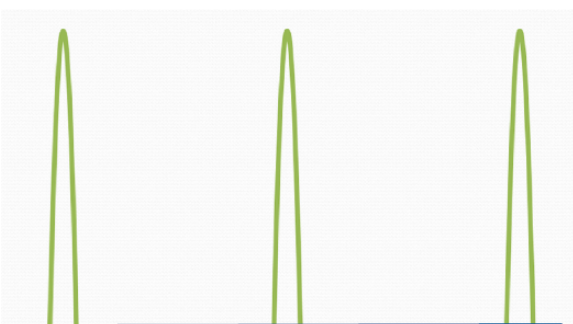


FIGURE 5. The pitch of an exposed pattern narrowed with STED is not changing, resulting in a sparse pattern of narrow features.

This grid of narrow features spaced at Rayleigh pitch can be filled by successive scans resulting in a final pattern which appears to violate the Rayleigh criterion for the exposure wavelength used, but actually has not, since the final pattern is written time shifted using successive scans.

OPTICALLY DEFINED CUT-PATTERNS BEYOND THE RAYLEIGH LIMIT

The STED effect may also benefit the resolution of photon beamlets used for maskless optical direct writing (ODW). Surrounding an exposure beam with matrixed depletion beams results in a narrowed exposure spot, which we project to be capable of writing features of 10 nm CD or less. This approach can be implemented in a highly parallel fashion, allowing random patterns to be written with a large array of independently controlled beamlets.

Writing line-cut patterns with photons rather than electrons has significant advantages, eliminating numerous serious complications of e-beam based systems. Photons do not interact with each other, eliminating electron-electron effects particularly at high beam currents. Maximum beam intensity is now set by the materials limitation of the resist, not by the limitations of electron-electron interactions, which are column design dependent, particularly at high beam currents. In addition, the need for dynamic control of beamlet location dependent on the condition of neighboring beams is eliminated.

REFERENCES

- [1] Dick James – Chipworks Blog http://www.electroiq.com/blogs/chipworks_real_chips_blog/2012/04/intel-s-22-nm-trigate-transistors-exposed.html
- [2] Michael C. Smayling, Hua-yu Liu, Lynn Cai Low k_1 Logic Design using Gridded Design Rules; SPIE Advanced Lithography Conference 2008; 6925-68
- [3] Yan Borodovsky, "MPProcessing for MPProcessors", Maskless Lithography and Multibeam Mask Writer Workshop (2010)
- [4] Hell, S. W.; Kroug, M. (1995). "Ground-state depletion fluorescence microscopy, a concept for breaking the diffraction resolution limit". *Applied Physics B: Lasers and Optics* **60** (5): 495–497.
- [5] R. Menon and H. I. Smith, "Absorbance-modulation optical lithography," *J. Opt. Soc. Amer. A* **23**, 2290-2294 (2006).
- [6] J. S. Petersen et al.; Simulation study of LWR bounding of depth of focus of various lithographic techniques: interference, optical projection, EUV, e-beam and hybrid complementary lithography, and a proposal for a new production interference tool, SPIE 2012; [8326-28]

Authors Index

Acome, E.	4	Langelaar, Mathijs,	32
Allezy, Arnaud, P.	4	Liebers, Melvin, J.	45
Anderson, Erik, H.	4	Lu, Xiaodong	49
Arneson, David, A.	45	Lu, Yang.	105
Benk, Markus, P.	4	Lüerß, Bernd	91
Bifano, Thomas, G.	105	MacDougall, J.	4
Binnard, Michael	8	Markle, David, A.	109
Brinksmeier, Ekkard	68	Marsh, Eric, R.	45
Chao, Weilun, L.	4	Meier, Axel	68
Cheng, Jianrui	101	Milanovic, V.	4
Chi, Feng	101	Mochi, Iacopo	4
Choi, Jin	22	Mock, Christopher, Daniel	89
Chu, Kevin, C.	73	Mokaberi, Babak	22
Clyne, Joshua,	16	Munnig Schmidt, Robert-Han.	95
Cork, C. W.	4	Naulleau, Patrick	4
Cork, W.	4	Nayfeh, Samir, Ali	16
Di Regolo, Joseph, A.	16	Ni, Kang.	42
Dow, Thomas, A.	64	Nimmakayala, Pawan, Kumar.	22
Dumitrescu, Eugen.	91	Nowak, W., John.	64
Ellis, Jonathan, D.	36	Oberfell, Joachim	89
Fujiwara, Tomoharu	8	Oss, Daniel, D.	45
Gillmer, Steven	36	Peters, Hugo, Jacobus	80
Gläbe, Ralf.	68	Peterson, John, S.	109
Glöss, Rainer.	89	Ramsay, Euan	105
Golda, Janice	3	Raub, Alex, K.	109
Goldberg, Bennett, B.	105	Rekawa, Senajith, Bandara.	4
Goldberg, Kenneth, A.	4	Renkens, Marcel, J. M.	53
Goldsmith, Richard, J.	59	Saad, Mohamed, El-Sayed	17
Greenway, Robert, T.	109	Saathof, Rudolf	95
Haber, Aleksandar.	95	Safreno, Ty, F.	59
Hale, Layton, C.	16	Sahin Nomaler, Funda.	53
Hamatani, Masato	8	Schönemann, Lars	68
Heinisch, Josef	91	Schönhoff, Ulrich	83
Hendel, Rudi, H.	109	Schumaker, Philip	22
Hocken, Robert, J.	17, 42	Shiba, Yuji	8
Hooijkamp, Evert, Cente.	80	Shibazaki, Yuichi	8
Jordan, Scott, C.	27	Smayling, Mike, C.	109
Kelley, Troy	59	Smith, Nathan, S.	4
Knapp, Byron, R.	45	Smith, Richard, C. G.	36
Köklü, Faith, Hakan	105	Spronck, Jo, W.	95
LaBrake, Dwayne	22	Sreenivasan, S., V.	22
Langehanenberg, Patrik	91	Stickler, Danie	91

Stockbridge, Christopher, R.	105
Tarbutton, Joshua	36
Toma, Adrian, A.	53
Tsao, Tsu-Chin	73
Uehara, Yusaku	8
Ummethala, Upendra	16
Ünlü, M., Selim	105
Usman, Irfan-ur-rab	49
van Eijk, Jan	32, 80
van Every, E.	4
van Keulen, Fred	32, 80
van Lievenoogen, Anne	16
van Loo, Jerome	16
Vandyshev, Kostiantyn	32
Verhaegen, Michel	95
Wakamoto, Shinji	8
Wang, Chen	36
Wang, Yigang	73
Williams, Mark, E.	16
Wilson, Curtis, S.	76
Woody, Shane, C.	36
Wu, Liwei	101
Ye, Zhengmao	22
Zdanowicz, Erik, M.	64
Zhang, Xiaowen	101
Zhang, Zhigang	101

ASPE 2012 Sustaining Corporate Sponsors



3M Company
St. Paul, MN 55144
Phone: (651) 737-3790
www.mmm.com



ADCOLE Corporation
669 Forest Street
Marlborough, MA 01752
Phone: (508) 485-9100
Fax: (508) 481-6142
www.adcole.com



Aerotech, Inc.
101 Zeta Drive
Pittsburgh, PA 15238-2897
Phone: (412) 963-7470
Fax: (412) 963-7459
www.aerotech.com



Agilent Technologies
Agilent Technologies, Inc.
5301 Stevens Creek Boulevard
P.O. Box 58059
Santa Clara, CA 95052-8059 USA
Phone: (877) 424-4536
www.home.agilent.com

alicon

Alicona
1261 Humbracht Circle
Suite G
Bartlett, IL 60103 USA
Phone: (630) 372-9900
www.alicon.com



AMETEK-Precitech, Inc.
44 Blackbrook Road
Keene, NH 03431
Phone: (603) 357-2511
Fax: (603) 358-6174
www.precitech.com



We make it visible.

Carl Zeiss Industrial Metrology LLC
6250 Sycamore Lane North
Maple Grove, MN, 55369
Phone: (663) 744-2400
www.zeiss.com/metrology



Chardon Tool
115 Parker Court
Chardon, OH 44024
Phone: (440) 286-6440
Fax: (440) 286-7165
www.ChardonTool.com

Cranfield Precision

Cranfield Precision
Division of Cinetic Landis Ltd.
Woburn House
3 Adams Close
Kempston, Bedford, MK42 7 JE
United Kingdom
Phone: +44 (0)1234 312820
www.cranfieldprecision.com



DELTA TAU
Data Systems, Inc.
NEW IDEAS IN MOTION ...

Delta Tau Data Systems
21314 Lassen Street
Chatsworth, CA 91311 USA
Phone: 818-998-2095
Fax: 818-998-7807
www.deltatau.com



K & Y Diamond
2645 Diab St. Laurent
Quebec H4S 1E7
CANADA
Phone: (514) 333-5606
Fax: (514) 339-5493
www.kydiamond.ca



Lion Precision
563 Shoreview Park Road
St. Paul, MN 55126-7014
Phone: (651) 484-6544
Fax: (651) 484-6824
www.lionprecision.com



Makino
7680 Innovation Way
Mason, OH 45040
Phone: (513) 573-7200
Fax: (513) 573-7360
www.makino.com



Mitutoyo America Corporation
945 Corporate Boulevard
Aurora, IL 60504-9102
Phone: (630) 723-3619
Fax: (630) 978-6471
www.mitutoyo.com



Moore Nanotechnology Systems LLC
230 Old Homestead Highway
Swansey, NH 03446
Phone: (603) 352-3030
www.nanotechsys.com



nPoint, Inc.
3030 Laura Lane, Suite 100
Middleton, WI 53562 USA
Phone: (608) 824-1770
www.npoint.com



Professional Instruments Company
7800 Powell Road
Hopkins, MN 55343
Phone: (952) 933-1222
Fax: (952) 933-3315
www.airbearings.com



Specialty Components, Inc.
14 Village Lane
Wallingford, CT 06492
Phone: (203) 284-9112
Fax: (203) 672-0371
www.specialtycomponents.com



Trust Automation, Inc.
143 Suburban Road
San Luis Obispo, CA 93401
Phone: (805) 544-0761
Fax: (805) 544-4621
www.trustautomation.com

ASPE 2012 Corporate Sponsors

UnivBruker Nano Surfaces Business

2650 East Elvira Road
Tucson, AZ 85706-7123
Phone: (520) 741-1044
www.bruker-axs.de/nano.html

Corning Inc.

Corning, NY 14831
Phone: (607) 974-3842
www.corning.com

Contour Fine Tooling, Inc.

143 Jaffrey Road
Marlborough, NH 03455
Phone: (603) 876-4908
Fax: (603) 876-4911
www.contour-diamonds.com

nanoPrecision Products, Inc.

411-B Coral Circle
El Segundo, CA 90245
Phone: (310) 773-3550
www.nanoprecisionproducts.com

Center for Precision Metrology

University of North Carolina at Charlotte
9201 University Blvd.
Charlotte, NC 28223
Phone: (704)-687-8499
www.cmp.uncc.edu

Zygo Corporation

Laurel Brook Road
Middlefield, CT 06455-0448
Phone: (860) 347-8506
Fax: (860) 347-8372
Toll-free: (800) ZYGO-NOW

Volume 53

ISBN 978-1-887706-60-5